Low Cost portable ECG Data Acquisition System

Manas Anant Savkoor

A Thesis Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

Department of Electrical Engineering

June 2013

Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

(Signature)

ManasAnantSavkoor

(– Student Name –)

EE11M05

(Roll No)

ECG by Manas Anant
abad

Approval Sheet

This Thesis entitled Data Acquisition Block for a portable low cost ECG by Manas Anant Savkoor is approved for the degree of Master of Technology from IIT Hyderabad

(Chandra Shekhar Sharma) Examiner
Dept. of Chemical Eng
IITH

(G.V.V. Sharma) Examiner
Dept. of Electrical Eng
IITH

(Ashmi deb Dutta) Adviser
Dept. of EE Eng
IITH

(AMIT ACHARYYA) Adviser
Dept. of ---------- Eng
IITH

(ch. sobhan baby) Chairman
Dept. of CS Eng
IITH
21/06/2017

Sharma) Examiner
Dept. of Chemical Eng
IITH

) Examiner
Dept. of Electrical Eng
IITH

) Adviser
Dept. of EE Eng
IITH

) Adviser
Dept. of ---------- Eng
IITH

baby) Chairman
Dept. of CS Eng
IITH
21/06/20

Approval Sheet

This Thesis entitled Low Cost portable ECG Data Acquisition System by Manas Anant Savkoor is approved for the degree of Master of Technology from IIT Hyderabad

———————— (Dr. Chandrashekar Sharma) Examiner Dept. of Chem Eng IITM

———————— (Dr. G V V Sharma) Examiner Dept. of Elec. IITH

———————— (Dr. Ashudeb Dutta) Adviser Dept. of Elec Eng IITH

———————— (Dr. Amit Acharyya) Co-Adviser Dept. of Elec Eng IITH

———————— (Dr. Sobhan Babu) Chairman Dept. of Comp Eng IITH

Acknowledgements

I would like to thank “my” advisers Dr. Ashudeb Dutta and Dr. Amit Acharyya. It was a pleasure to work with both the advisors who encouraged me to discuss, explore and validate. The opportunity to create a system as a promising solution for a pertinent problem is rarely available and I hope I have succeeded in providing a good start as well as listed possible tools, pitfalls for those who follow. Apologies to both my guides if I have crossed any line in my enthusiasm. I would also like to thank Dr. Soumya Jana for the opportunity given. Sir, CS is a wonderful topic and I was glad to be able to apply it. Dr. Shiv Gobind Singh was the first faculty I met in our group, thank you sir, you have always encouraged us. I also am thankful to my course profs. Dr. KSRM, our HoD Dr. Zafar Ali Khan and Dr. Siva Rama Krishna. Thankful to the profs under whom I was the TA, Dr. Vaskar Sarkar and Dr. G V V Sharma, Dr. Sumohana too.

I would like to thank the lab incharge Jyothi Rani, Ramesh, Tirupathi and Suresh. For the enthusiasm and willingness to learn which inspired me I thank Vamshi, Ronak, Mayank, Manhar, Kapil and Thumathi. I wish to thank Aravinth, Hafeez, Saptarishi, Tamal, Durgaprakash, Nisha, Shabana, Aneesh! I thank Pankaj Jha for the inspiration and motivation. To my juniors best wishes, and in particular to Utkalika and Sandeep. A contribution here can make a huge difference.

I thank my batchmates Shyam, Nagaveni, Pramod, Raman, Rohit, Ramesh, Karthik, Sridhar, Jeetendra, Meher, Yatendra. To Roopak R Tamboli whom is my batchmate and with whom I had the opportunity to work along thanks, I have enjoyed our discussions, hope to have more.

I would like to thank the Director, the academic staff and IIT-Hyderabad for the opportunity to interact with so many people.

To forget is easy to forgive is difficult, I request my peers, seniors, profs to forgive me for any inadvertent mistake committed on my part.

I now wish to say thank you to my parents Mrs. Shantha Savkoor and Mr. A G Bhat Savkoor and my brother Ullas who supported and encouraged me, I also thank tall Vinu Dada along with Manthu, Mave, Bapa, Pacchi, Mam, Mami, Akku and Dada, Vahini for the support, encouragement. too.

Dedication

To Bharat

Abstract

A design strategy for the data acquisition block of a portable ECG machine for affordable remote CVD detection and diagnosis is proposed. It exploits the ECG property that most of the signal is concentrated within 20 Hz. Using this system one can achieve a low Nyquist data rate of 50 samples/sec. With Data Acquisition System designed one can also perform Irregular Sampling and using Compressive Sensing recover the signal. Using three such boards 3 ECG leads were simultaneously sampled both using Nyquist sampling and Irregular sampling. The cost of the one single board comes to Rs. (83+300) 383 and that of 3-Lead to Rs. (249 +500) 749. The Microcontroller board cost is not included as it was given free of cost.

Contents

Chapter 1

Introduction

The World Health Organization (WHO) has six strategic objectives; one of the strategic objectives of the WHO is to prevent and reduce disease, disability and premature death from chronic non-communicable conditions, mental disorders, violence and injuries [1]. To achieve this objective it publishes health statistics from nearly 194 countries to help better prepare and achieve its goals. The division of noncommunicable diseases (NCDs) at the Indian Council of Medical Research (ICMR) was identified as the nodalpoint for the surveillance of NCDs and their risk factors by WHO. The data collected in India is done by the Integrated Disease Surveillance Project (IDSP) survey in India which is carried out by the Indian Council of Medical Research (ICMR) on behalf of the Minstry of Health, Govt. of India.with funding from World Bank [17]. According to the World Health Statistics 2012 report out of 57 million global deaths in the standard year 2008, 36 million died from noncommunicable diseases (NCDs) of which 48% died from cardiovascular diseases (CVDs) [2].

CVDs are the number one cause of death globally, with 80% of CVD deaths taking place in low and middle income countries like India [3]. In India mortality due to CVDs has increased from 25% to 32.73% in just five years. [4]. One disturbing fact in all theses figures is while in higher income countries CVDs affect non-working population, in India and similar countries, CVDs are the cause of death for nearly 1/3 of the working population; this intern has serious spillover effects. Apart from this disturbing fact due to the inadequate primary health care centres, the cost of treatment and monitoring is prohibitive to the general masses. In the report of 2013, against WHO recommended norms of 23 healthworkers per 10, 000 population in India there are 6.5 doctors and 10 nurses. [4, 5].

An Electrocardiogram (ECG) is used to detect, diagnose and monitor CVDs. However the State of the Art Equipment (SotA) used to obtain it is bulky, power hungry and requires handling by trained healthcare professionals. Coupled with lack of adequate infrastructure and insufficient number of healthcare professionals and costly equipment it leads often to detection at late stages of the diseases, resulting in prohibitive costs of treatment and sundry expenses. But the majority of the people who have died in India and similar countries due to CVDs alone which is nearly 33% is in between the ages of 30-70. This segment is the workforce of the country. And if a country has to prosper then its workforce must be in pink of health. While this is the average statistics, in the rural countryside the figures become even more worse. In a country like India which has 70% population in rural areas, the cost of succumbing to such diseases is a very dangerous proposition.

Technology and engineering are buzz words. Technology refers to the making, modification,

usage, and knowledge of tools, machines, techniques, crafts, systems, and methods of organization, in order to solve a problem, improve a preexisting solution to a problem, achieve a goal, handle an applied input/output relation or perform a specific function [6]. Engineering is the application of scientific, economic, social, and practical knowledge in order to design, build, and maintain structures, machines, devices, systems, materials and processes. Hence by combining medicine and technology using engineering one must find a solution that meets the need for CVD's detection, diagnosis and monitoring.

One promising solution is Telehealth, and in it, Telecardiology [8, 9]. One of the oldest known telecardiology system (teletransmission of ECG) was established in Gwalior, India in 1975 at GR Medical college by Dr. Ajai Shanker, Dr. S. Makhija, P.K. Mantri using indigenous technique for the first time in India [10].

However fixed line telephone has very low penetration in India. On the other hand, recently, the world has seen very high penetration rate of mobile phones in many countries across the globe [12]. In fact of all the 21st century technologies, mobiles have been most widely accepted. Thus, Telecardiology is increasingly being seen as a viable solution, with the help of a portable ECG Data Acquisition Block (DAB) in tandem with the mobile phone portable ECG machines can be designed so as to be affordable and easy to use. The challenge is to create a portable ECG data acquisition system which can detect, diagnose and monitor CVDs even in rural healthcare setup by a layman.

The portable ECG machines can form a part of a system which makes use of the existing telecommunication network to allow for remote or automated detection, diagnosis and improvement. Significant work is going on in making such a system in terms of fine-tuning, report collection, parameter extraction and so on [13, 8, 10]. The overall scheme envisioned is shown below in Fig. 1.1. While a detailed review of the system, its sub-blocks will be given in section 1.3, there is not much work in making use of circuits made from standard components. The use of such components in the circuits will bring down the cost of the circuit both up-front and over the product's lifecycle.

1.1 ECG Signal details

The ECG signal is a physiological electropotential signal. Its being used to detect CVDs. The Appendix A has more details on ECG. The next section gives in detail the broad picture of the overall scenario envisioned for a portable ECG machine.

1.2 Remote/ Rural Healthcare System

The overall scheme envisioned is shown below in Fig. 1.1. The system is envisioned as a four-tier structure. They are described below:

I Patient End

II Nearest Healthcare Centre

III District Hospital

IV Pool of doctors

The descriptions for the four tiers are as follows:

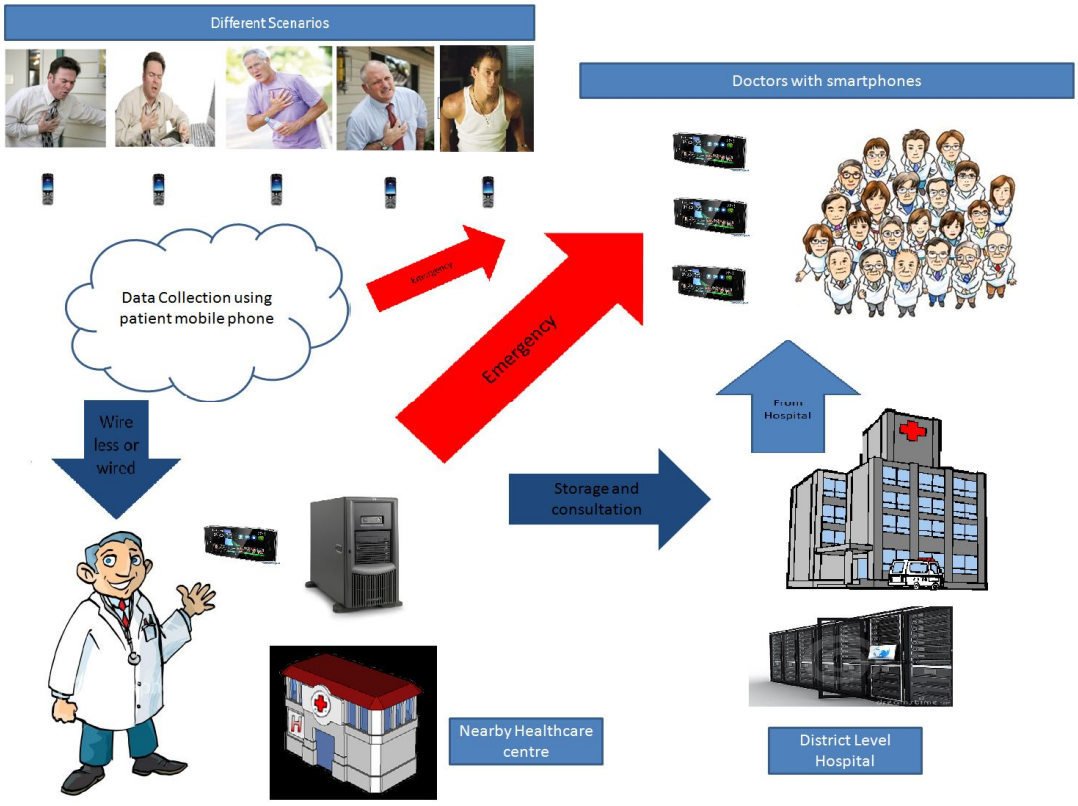


Figure 1.1: Overall picture of the ECG monitoring systems implementation.

1.2.1 Patient End

a Observations:

i The data is collected using a 3/4 lead + reference lead.

ii Data is converted into electrical form using sensors!

iii The data is in analog form and is noisy!

b Decisions:

a How the data from 3 leads is converted to a single stream!

b Type of processing done at front end.

c Should the interface between the patient and mobile phone be USB/ 3 mm Jack

d Power consumption needs to be recorded for the four scenarios:

e Complete software processing.

f Analog processing and software processing!

g Digital processing and then if required software processing!

h Analog/ Digital and software processing!

Based on the above the type of data acquisition system is decided! A single phone can be used by multiple users, one needs to devise a system that can effectively identify the patient and his/her data. Figure 1.2 shows the system at the patients end.

Figure 1.2: System at Patient End

1.2.2 Nearest Healthcare Centre

a Observations:

i We need the following in the nearest healthcare centre

i A simple computer.

ii A smart phone for the healthcare officer.

iii A doctor or healthcare worker or Anganwadi worker

ii The signals from the vicinity of the healthcare centre are sent to the healthcare centres computer.

iii The computer processes the signals and takes the necessary actions which may include:

i Alerting the healthcare officer

ii Sending the data to the District Hospital

iii Alerting the specialist doctors at the district hospital.

iv The healthcare worker may also collect the signals from the patients and feed it to the computer at the healthcare centre!

v The computer at the healthcare centre transmits the data to the district hospital either through internet or SMS/MMS.

b Decisions

i Amount of processing that needs to be done in the computer.

ii Procedure to send the data.

iii Allocation of patient ID to each person irrespective of mobile phone used.

iv Ensure one-to-one mapping of patient and his/her ECG data.

v Type of estimation and time of sending data to district hospital.

vi Protocol of sending data to patient, confirmation from patient.

vii Protocol of data transmission to district hospital and so on.

Figure 1.3 shows the system at the nearest healthcare centre.

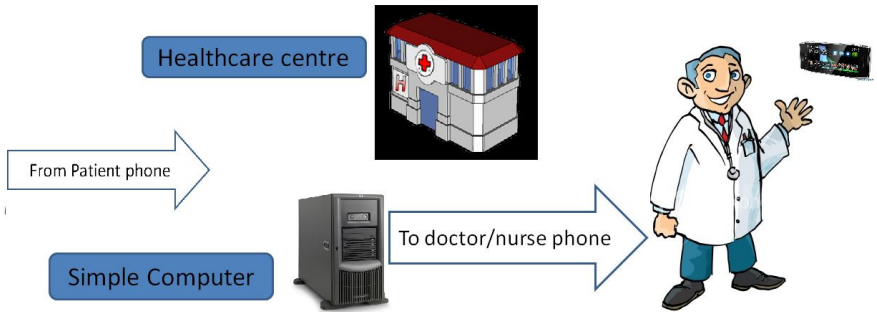


Figure 1.3: System at Nearest Healthcare Centre

1.2.3 District Hospital

a Observations:

i This is the primary data storage centre.

ii This place is assumed to have good power supply.

iii It contains a decent computer and a server for storage.

iv There are resident doctors present in the hospital and also from nearby hospitals.

v This place collects data from different healthcare centres and stores them for later perusal.

vi It performs estimation based on both present and previous data and based on the result acts accordingly.

b Decisions:

i Format of data storage and retrieval based on healthcare centre and family.

ii Estimation needs to be based on previous data and also current data.

iii Analyzed data will be sent to the doctors for approval.

iv The observations of the doctors are also noted down and collected along with patient data.

Figure 1.4 shows the system at the nearest district hospital.

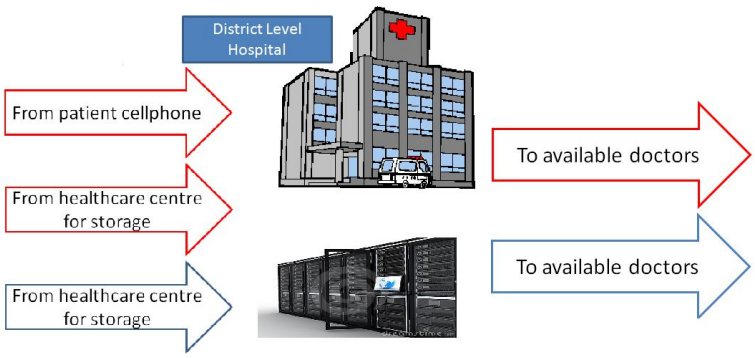


Figure 1.4: System at Nearest District Hospital

1.2.4 Pool of doctors

a Observations:

i Data is sent usually from the district hospital.

ii The sent data is in image form and in the required form.

iii Previous data recordings and observations are also sent based on doctors request.

iv It may be referred to a panel incase the software decides.

v The doctors prescription and advice are duly noted and recorded by the Smartphone provided to the doctors and sent to the district hospital.

b Decisions:

i Format data should be presented.

ii Observations of doctors to be recorded.

iii How the diagnosis is confirmed and sent to the patient.

iv In case the relevant specialist is not present in the hospital it needs to be sent into the nearest hospital.

Figure 1.5 shows the system at the nearest pool of doctors.

1.2.5 Overall Scheme

The four tier structure can be represented as shown in Fig. 1.6. This structure will be the basic unit of the health system envisaged as a honeycomb as shown in Fig. 1.7.

1.2.6 Working

Figures 1.8-1.10 give the flowchart which illustrates how the system is designed to work.

1.3 Aim

A low cost, easy to debug, portable ECG machine which uses cheap, easily available, commonly used electronic components, which with simple modification can be interfaced with any Analog to Digital Converter (ADC).

1.4 Literature Survey

One of the oldest telecardiology solutions (teletransmission of ECG) was established in Gwalior, India in 1975 at GR Medical college using an indigenous technique for the first time in India [10]. However due to lack of fixed line growth this had not proved successful. J P P Gomez in his report on Telemedicine and Telecardiology [8]summarizes the efforts in this field from the 1990s to early 2000s. Its quoted that the service started from telephone consultations along with development of portable telemedicine equipment and web-based services. The report states that the development of telecardiology has been in constant growth coupled with evolution of electronics and telecommunication. This is because bio-potential signals can be processed and transmitted through any network meant for voice or digital data communication.

Telecardiology is increasingly being seen as a viable solution, with the help of an ECG Data Acquisition Block (DAB) in tandem with the mobile phone portable ECG machines can be designed such to be affordable and easy to use to detect, diagnose and monitor CVDs even in rural healthcare setup. In 2005 the Ontario Telemedicine Network was found. One of its projects was to provide care for patients with Congestive Heart Failure (CHF) or Chronic Obstructive Pulmonary Disorder.

In 2011, one of the aims of the PHYSIONET/ Computing in Cardiology Challenge 2011 was to develop an efficient algorithm able to run within a mobile phone, that can provide useful feedback in the process of acquiring a diagnostically useful 12-lead ECG recordings. A joint collaboration between Narayana Hrudayalaya (one of Indias leading health-care providers) and Sana (an open-source, student-managed, mobile telemedicine group at MIT [13, 14] where Sana aims to develop innovative mobile technologies and on building local capacity through collaboration and education.

In general the work has been focused on the processing, parameter extraction, storage and removal. In Data Acquisition the portable ECGs begin from Rs. 30K. Semi-Custom ICs and standard components are used to make the boards. In ASIC solutions R. F. Yazicioglu [18] has developed a 30 µW analog signal processor which can be used for ambulatory purposes. Wei [19] proposes a general purpose tunable AFE for bio-potential signals recording systems. ASIC level solutions if mass manufactured will capture signals at poorer SNR and can perform more complicated processing. Time to develop such solutions is long, these general tend to be custom designs in terms

of analog circuit design and semi-custom in terms of digital design. Moreover the absence of an indigenous ASIC is a significant drawback. Thus one may identify the following challenges:

- Further reduction in Nyquist sampling rate by exploiting the features of the ECG signal.
- Also usage of new techniques to efficiently remove Power Line Interference and high frequency artifacts.
- A novel and simple design that uses cheap easily available commonly used standard electronic components. Modularity in design which renders for easy debug, robustness and ease of usage
- Ability to view, record and monitor a three ECG lead data simultaneously by a cheap and yet robust system.
- Enabling the use of the concept of irregular sampling (IR) and recovery of signal using Compressive Sensing (CS) which are relatively new emerging fields.
- Harnessing the power of USB on the go.
- Ability to harness IoT i.e. Internet of Things.
- Merging emerging technologies like IR, CS, IoT.
- Developing an ASIC which can be reconfigurable both in Analog, Digital and re-programmable in Software.

Thus while significant work is going on in parameter extraction, processing in ASIC level as well as using the mobile technology. Developing a simple low cost, easy to debug portable ECG machine which can be used in tandem with a mobile phone has not received much attention. In this thesis we attempt to build such a system which can be built using cheap, easily available, commonly used electronic equipment. The design has been implemented to bring in modularity such that faulty part can be easily identified using a simple backward trace. Furthermore the parameters of the circuit have been made robust.

1.5 Contribution of the Thesis

This work focuses on the design and implementation of an ECG Data Acquisition system . The main contributions of this research are as follows:

- A comprehensive analysis on the frequency content in ECG signal.
- Reduction in Nyquist sampling rate to around 50 $\frac{\text{samples}}{\text{s}}$ by bandlimiting to 25 Hz.
- Removal of Power Line Interference and high frequency artifacts.
- A novel and simple design that uses cheap easily available commonly used standard electronic components.
- Modularity in design which renders for easy debug, robustness and ease of usage.

- Demonstrating successfully, the use of the concept of irregular sampling and recovery of signal using Compressive Sensing.
- Ability to record three ECG lead data simultaneously @ 1000 Hz.
- Ability to record three ECG lead data simultaneously using the emerging IR and CS technique.
- An empirical study on the best possible mother wavelet one can use for sparsest representation.
- Use of the CORTEX M3 Microcontroller based on MBED platform is to demonstrate easy of use with low power ARM based chips.
- The other advantage is usage of USB on the go feature as well as future possibility of using it on IoT i.e. Internet of Things.

In the next chapter we first introduce the about the study done on the standard ECG signals and then the tabulated results of the study are present in the end.

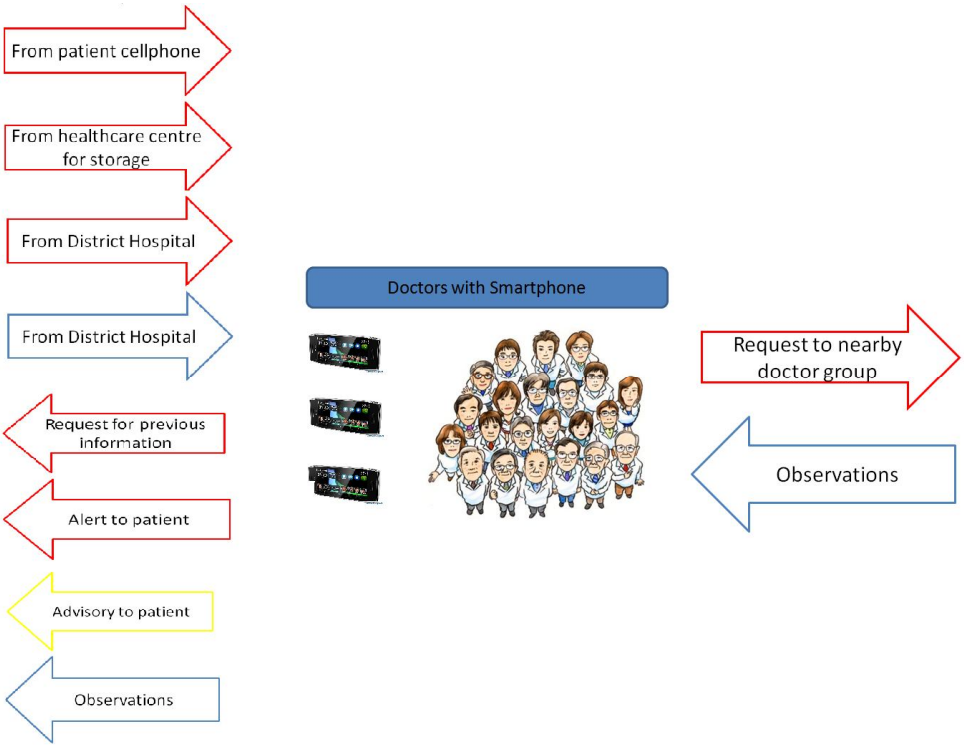


Figure 1.5: Schematic representation of nearest pool of doctors

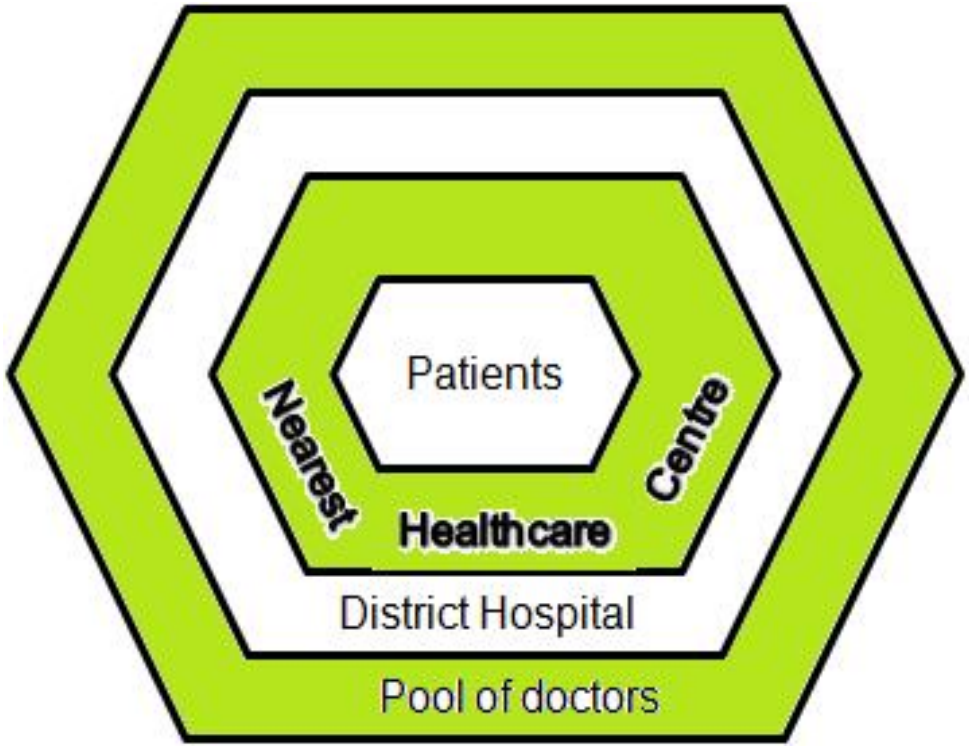


Figure 1.6: Schematic representation of the four tiers

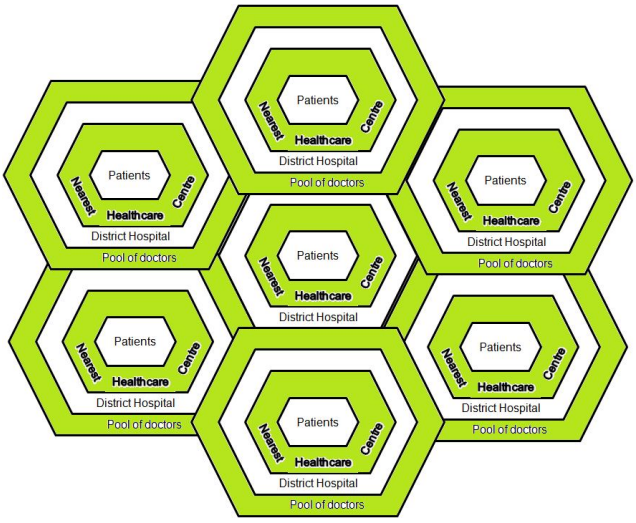


Figure 1.7: Schematic representation of the overall healthcare system as a Honeycomb structure

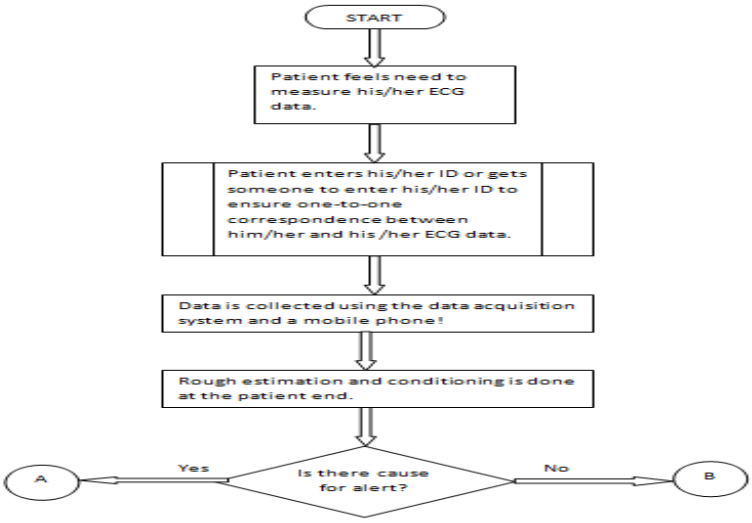


Figure 1.8: Part 1 of the flowchart representation of the working of the system for one ECG recording

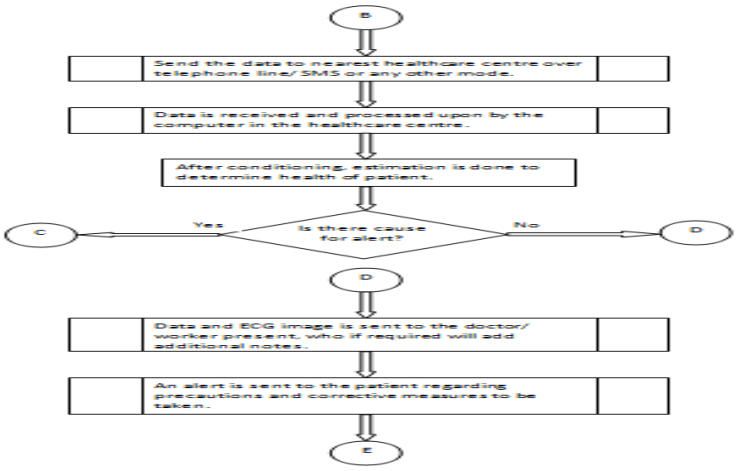


Figure 1.9: Part 2 of the flowchart representation of the working of the system for one ECG recording

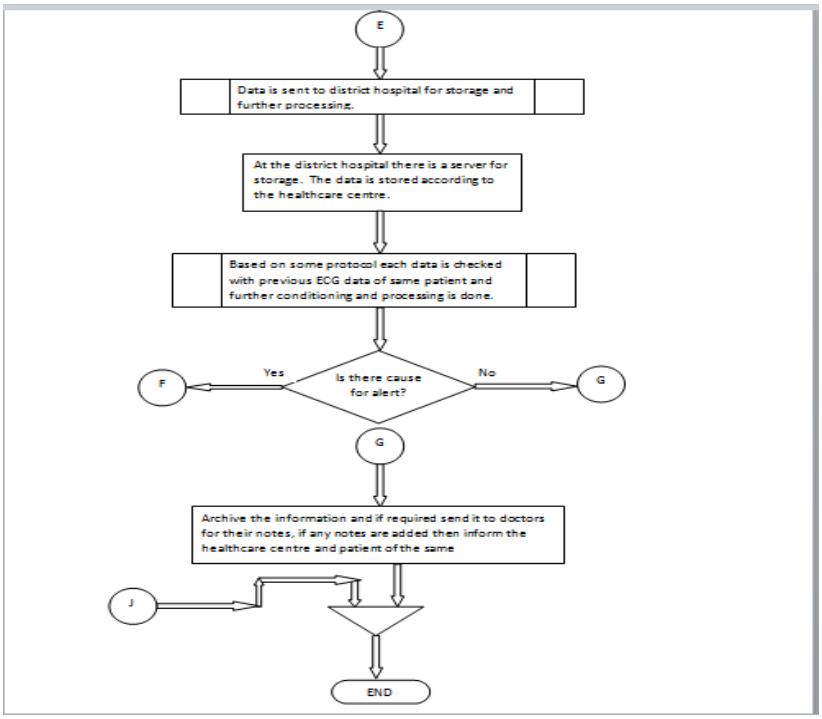


Figure 1.10: Part 3 of the flowchart representation of the working of the system for one ECG recording

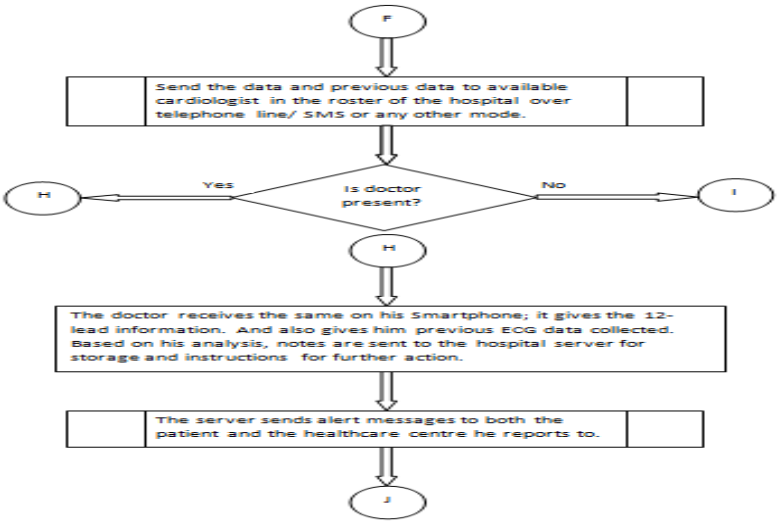


Figure 1.11: Part 4 of the flowchart representation of the working of the system for one ECG recording

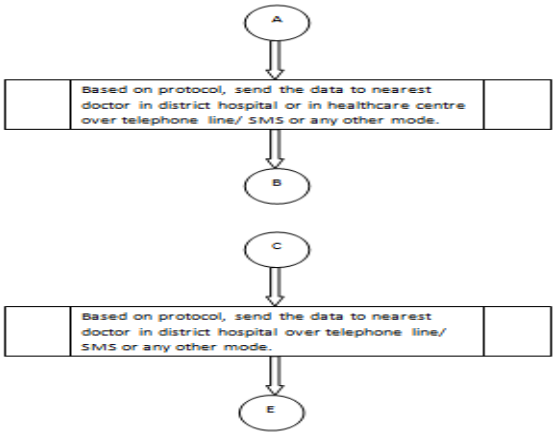


Figure 1.12: Part 5 of the flowchart representation of the working of the system for one ECG recording

Chapter 2

Study on Bandlimiting

A State-of-the-Art (SotA) ECG system can be divided into three blocks The DAB, to acquire the signal; the signal processing block for signal smoothening, removal of high frequency and power line interference (PLI) noise, feature extraction and the communication block to transmit the data to a medium accessible and in a format desirable to user and health workers. Current research and innovation thrust is on the last two blocks [20, 21, 22, 23, 24]. In the DAB, research is focused on acquiring multi-parametric physiological signals, removing PLI and high frequency noise, along with reduction in power consumption, thereby increasing the complexity of the system and adding extra burden to the processing and communication block [18, 25, 26, 27]. Through the proposed design strategy which will be discussed next, an affordable solution for DAB dedicated to ECG under rural CVD health monitoring is proposed. Here we propose a design strategy for DAB to record ECG signal with small BW (25 Hz) which will have direct connectivity with the mobile phones of the users as well as the health workers. We have used 231 ECG records of patients covering 23 conditions from the PhysioNet [28] database (PTBDB) [29] for validation. The simulation results of bandlimiting the ECG lead signals as mentioned in section previous and current chapters shown in Table 2.1. We also calculated the mean (μ) and standard deviation (std(E)) of the difference between the original and bandlimited signal across 23 conditions and 231 ECG records. As for an example in the Bundle Branch Block condition, 11 ECG records have been analyzed (row 1, Table 2.1) and the average values of the performance evaluation metrics are tabulated. The same is done for the other conditions, the last row has the average values computed across 231 ECG records. Furthermore a pictorial description of what we did for each ECG record can be seen in Fig. 2.1 i.e before and after bandlimiting from a to f and p to u respectively. Thus on visual inspection one can see that there is no detectable change from the original signal to the bandlimited signal. Given below are the performance evaluation metrics used.

Performance Evaluation Metrics Following four metrics are used in this study: Rsquare (R^2)[30]: measure of the energy content retained, Correlation: measure of the structural similarity, Regression: measure of the amplitude similarity [31]. In addition to these, the Bland-Altman (BA) [32, 33]: gives a measure of the number of samples in the signal whose difference is greater than the accepted limit. The corresponding mathematical expressions are given below:

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (s(i) - b(i))^2}{\sum_{i=1}^{N} (b(i) - \mu(b))^2}$$

$$corr = \frac{E[(s-\mu_s)(b-\mu_b)]}{std(s)*std(b)},\ s = regr * b \text{ and}$$

$$BA = \frac{\sum_{i=1}^{N}((s(i) - b(i)) < |\mu_{(s-b)} + 1.96 * std(s-b)|)}{\sum_{i=1}^{N}(s(i) - b(i))}$$

where s=reconstructed, b=original signal, both of length N.

Now the time domain and frequency domain representation of one of the records from PTBDB [29] are shown in Fig. 2.1 (a), (b), (c) and (d), (e), (f) respectively. In the insets shown in (a), (b) and (c) we can see the presence of noise, (p) to (u), the original (blue), bandlimited (green) and error (red) signals respectively are superimposed and shown, these were obtained after bandlimiting using FFT technique on the below mentioned ECG record; (p), (q), (r) are the time, (s), (t), (u) are frequency domain representation respectively. The insets in (p), (q) and (r) give a magnified look at the reconstructed signal tracing the original signal. Insets in (s), (t) and (u) show the relative amplitude reduction around 25 Hz and different amplitude levels in the three leads. These plots are from ECG Record s0364lre of patient 171 who is classified as having a Bundle Branch Block.

The insets shown in Fig. 2.1 show the presence of the noise at the time the signals were captured. These standard ECG signals were generally captured using a 16-bit microcontroller (µC) using a 12-bit or a 10-bit ADC. The PTB database records have a bit-width of 16 and were sampled at the rate of 1000 Hz. This is because of the need to be able to study Heart Rate Variability (HRV).

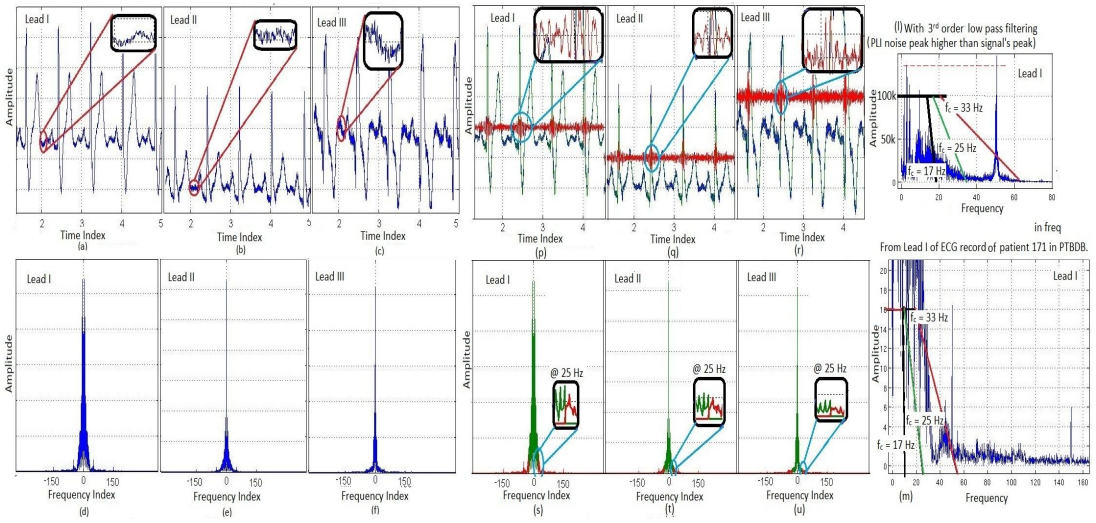


Figure 2.1: The ECG lead data are part of the ECG Record s0364 LRE of Patient 171. This patient was categorized into the Bundle Branch Block category. This was taken from PTBDB [29].The ECG lead values are not drawn to the same level. The baseline in each of them is near 0 V. (l) has the frequency content of a Lead I ECG signal filtered with a cascaded 3rd order filter, on this for illustration purpose three frequency roll-offs of LPF's at different frequencies are superimposed. (m) has the same illustration on the frequency content of Lead I ECG signal shown in (d) from PTBDB.

Where the power frequency is 30 Hz, we propose a design strategy for DAB to record ECG signal with small BW (30 Hz) which will have direct connectivity with the mobile phones of the users as well as the health workers. We have used the same 231 ECG records of patients covering 23 conditions from the PhysioNet [28] database (PTBDB) [29] for validation. The simulation results of bandlimiting the ECG lead signals as mentioned in section previous and current chapters shown in

Table 2.1: Tabulation of average values of metrics comparing the original and reconstructed signal having bandwidth 25 Hz. BA stands for Bland-Altman, E is error or difference between the two signals. Data Source: PTBDB[29], PhysioNet[28]

Condition(Record)	Lead I data					Lead II data					Lead III data				
	R^2	corr	regr	BA	μ±std(E)	R^2	corr	regr	BA	μ±std(E)	R^2	corr	regr	BA	μ±std(E)
Bundle branch block (11)	98.004	98.975	0.988	94.918	0 ± 0.023	97.079	98.502	0.991	95.271	0 ± 0.031	94.697	97.275	0.987	95.3	0 ± 0.025
Cardiomyopathy (11)	96.172	98.031	0.975	94.529	0 ± 0.026	96.675	98.292	0.99	94.996	0 ± 0.027	96.009	97.948	0.983	94.818	0 ± 0.033
Dysrhytmia (10)	95.416	97.646	0.965	95.158	0 ± 0.026	97.222	98.579	0.985	95.54	0 ± 0.028	95.232	97.544	0.975	96.084	0 ± 0.021
Healthy Control directory (11)	95.505	97.698	0.975	94.251	0 ± 0.024	95.611	97.751	0.979	95.049	0 ± 0.038	93.818	96.818	0.968	95.12	0 ± 0.032
Heart Failure (3)	98.519	99.236	0.995	94.6	0 ± 0.031	98.517	99.236	0.995	94.427	0 ± 0.029	90.988	95.229	0.975	94.427	0 ± 0.03
Myocarditis (2)	97.181	98.558	0.984	94.169	0 ± 0.032	97.936	98.941	0.992	94.694	0 ± 0.024	94.923	97.384	0.988	94.531	0 ± 0.027
Myocardial Hypertrophy (7)	93.513	96.659	0.985	94.947	0 ± 0.025	94.973	97.401	0.99	94.788	0 ± 0.033	94.494	97.125	0.971	95.061	0 ± 0.037
myo infac ant lat (15)	93.513	96.659	0.985	94.947	0 ± 0.025	94.973	97.401	0.99	94.788	0 ± 0.033	94.494	97.125	0.971	95.061	0 ± 0.037
myo infac ant (19)	94.425	97.138	0.974	94.272	0 ± 0.025	95.012	97.441	0.981	94.933	0 ± 0.026	92.816	96.273	0.982	95.373	0 ± 0.027
myo infac ant sep lat (2)	99.228	99.593	0.999	95.05	0 ± 0.014	94.346	97.078	0.998	95.67	0 ± 0.028	97.313	98.623	0.996	94.88	0 ± 0.035
myo infac ant sep (31)	94.201	97.018	0.978	94.65	0 ± 0.026	95.019	97.422	0.989	95.025	0 ± 0.024	94.859	97.348	0.985	95.217	0 ± 0.024
myo infac inf lat (27)	95.087	97.481	0.976	94.021	0 ± 0.03	94.531	97.181	0.984	94.91	0 ± 0.029	96.722	98.317	0.994	94.717	0 ± 0.025
myo infac inf (32)	95.909	97.906	0.979	94.499	0 ± 0.025	96.205	98.058	0.987	94.858	0 ± 0.025	97.39	98.661	0.99	95.813	0 ± 0.021
myo infac inf pos lat (16)	95.074	97.462	0.974	94.874	0 ± 0.031	95.085	97.466	0.981	94.873	0 ± 0.026	95.474	97.676	0.983	94.838	0 ± 0.029
myo infac inf pos (1)	97.342	98.642	0.999	93.88	0 ± 0.017	98.813	99.385	0.999	94.1	0 ± 0.014	97.379	98.661	0.975	95.52	0 ± 0.013
myo infac lat (3)	93.529	96.688	0.981	94.213	0 ± 0.028	92.248	96.016	0.978	94.193	0 ± 0.037	87.25	93.377	0.966	94.947	0 ± 0.022
No acute infaction (11)	96.898	98.405	0.981	95.109	0 ± 0.017	98.214	99.08	0.989	95.395	0 ± 0.021	98.227	99.087	0.986	95.056	0 ± 0.026
myo infac pos lat (5)	96.61	98.262	0.983	96.48	0 ± 0.03	91.478	95.599	0.94	96.3	0 ± 0.031	94.734	97.29	0.973	95.56	0 ± 0.029
myo infac pos (4)	98.93	99.443	0.994	94.57	0 ± 0.019	98.371	99.162	0.992	95.985	0 ± 0.031	90.92	95.243	0.99	94.95	0 ± 0.033
Palpitation (1)	99.029	99.493	0.99	94.6	0 ± 0.016	96.833	98.384	0.969	96	0 ± 0.023	99.332	99.645	0.994	96.9	0 ± 0.016
Stable Angina (2)	89.987	94.842	0.939	94.89	0 ± 0.046	90.295	95.005	0.964	95.05	0 ± 0.037	84.982	92.103	0.953	95.78	0 ± 0.039
Unstable Angina (1)	99.647	99.804	0.997	94.92	0 ± 0.012	99.526	99.743	0.995	93.94	0 ± 0.017	98.553	99.254	0.987	94	0 ± 0.021
Valvular heart disease (6)	96.091	97.995	0.971	94.617	0 ± 0.035	98.087	99.017	0.985	94.123	0 ± 0.029	96.437	98.179	0.974	95.13	0 ± 0.034
Overall Average (231)	95.505	97.691	0.978	94.606	0 ± 0.026	95.768	97.822	0.985	95.001	0 ± 0.027	95.274	97.558	0.984	95.201	0 ± 0.027

Table 2.2. We again also calculated the mean (μ) and standard deviation (std(E)) of the difference between the original and bandlimited signal across 23 conditions and 231 ECG records. As for an example in the Bundle Branch Block condition, 11 ECG records have been analyzed (row 1, Table 2.2) and the average values of the performance evaluation metrics are tabulated. The same is done for the other conditions, the last row has the average values computed across 231 ECG records. Furthermore a pictorial description of what we did for each ECG record can be seen in Fig. 2.1 i.e before and after bandlimiting from a to f and p to u respectively.

In the next chapter we describe the circuit built which exploits this property.

Table 2.2: Tabulation of average values of metrics comparing the original and reconstructed signal having bandwidth 25 Hz. BA stands for Bland-Altman, E is error or difference between the two signals. Data Source: PTBDB[29], PhysioNet[28]

Condition(Record)	Lead I data					Lead II data					Lead III data				
	R^2	corr	regr	BA	μ±std(E)	R^2	corr	regr	BA	μ±std(E)	R^2	corr	regr	BA	μ±std(E)
Bundle branch block (11)	98.705	99.329	0.986	95.204	0 ± 0.016	96.995	98.458	0.97	95.256	0 ± 0.031	94.533	97.192	0.945	95.482	0 ± 0.025
Cardiomyopathy (11)	97.91	98.926	0.976	94.716	0 ± 0.018	96.588	98.247	0.966	95.091	0 ± 0.027	95.991	97.939	0.959	94.86	0 ± 0.033
Dysrhytmia (10)	97.098	98.511	0.969	95.502	0 ± 0.019	97.112	98.524	0.97	95.598	0 ± 0.028	95.165	97.51	0.951	96.136	0 ± 0.021
Healthy Control directory (11)	97.879	98.913	0.976	94.327	0 ± 0.017	95.585	97.738	0.955	95.031	0 ± 0.038	93.814	96.816	0.938	95.149	0 ± 0.032
Heart Failure (3)	98.5	99.227	0.984	95.327	0 ± 0.022	98.372	99.163	0.983	94.86	0 ± 0.029	90.992	95.231	0.91	94.433	0 ± 0.03
Myocarditis (2)	98.847	99.402	0.986	94.211	0 ± 0.018	97.913	98.93	0.979	94.691	0 ± 0.024	94.917	97.381	0.949	94.526	0 ± 0.027
Myocardial Hypertrophy (7)	95.452	97.669	0.951	95.191	0 ± 0.019	94.926	97.377	0.948	94.816	0 ± 0.033	94.44	97.098	0.944	95.065	0 ± 0.037
myo infac ant lat (15)	95.452	97.669	0.951	95.191	0 ± 0.019	94.926	97.377	0.948	94.816	0 ± 0.033	94.44	97.098	0.944	95.065	0 ± 0.037
myo infac ant (19)	97.134	98.535	0.968	94.425	0 ± 0.017	94.947	97.408	0.949	94.952	0 ± 0.026	92.774	96.252	0.927	95.364	0 ± 0.027
myo infac ant sep lat (2)	99.637	99.798	0.996	95.17	0 ± 0.017	94.257	97.032	0.942	95.72	0 ± 0.028	97.266	98.599	0.972	95.02	0 ± 0.035
myo infac ant sep (31)	96.609	98.265	0.962	94.766	0 ± 0.018	94.91	97.367	0.948	95.158	0 ± 0.024	94.705	97.268	0.946	95.365	0 ± 0.024
myo infac inf lat (27)	97.186	98.554	0.969	94.436	0 ± 0.02	94.361	97.089	0.943	95.035	0 ± 0.029	96.582	98.245	0.965	94.868	0 ± 0.025
myo infac inf (32)	97.826	98.886	0.975	94.701	0 ± 0.017	96.127	98.018	0.96	95.023	0 ± 0.025	97.31	98.621	0.972	95.844	0 ± 0.021
myo infac inf pos lat (16)	96.97	98.446	0.966	95.099	0 ± 0.022	95.013	97.429	0.949	94.956	0 ± 0.026	95.417	97.647	0.954	94.84	0 ± 0.029
myo infac inf pos (1)	98.391	99.173	0.981	94.28	0 ± 0.023	98.561	99.258	0.986	95.28	0 ± 0.014	96.297	98.111	0.963	96.38	0 ± 0.013
myo infac lat (3)	96.317	98.124	0.956	94.507	0 ± 0.016	92.198	95.99	0.92	94.253	0 ± 0.037	87.214	93.359	0.872	94.96	0 ± 0.022
No acute infaction (11)	97.406	98.667	0.973	95.098	0 ± 0.016	98.145	99.046	0.981	95.551	0 ± 0.021	98.161	99.053	0.981	95.133	0 ± 0.026
myo infac pos lat (5)	97.629	98.785	0.975	96.364	0 ± 0.024	91.417	95.567	0.914	96.28	0 ± 0.031	94.579	97.211	0.946	95.64	0 ± 0.029
myo infac pos (4)	99.404	99.682	0.993	94.69	0 ± 0.012	98.356	99.154	0.983	95.98	0 ± 0.031	90.895	95.231	0.908	94.89	0 ± 0.033
Palpitation (1)	99.537	99.748	0.995	93.76	0 ± 0.043	96.785	98.359	0.968	95.86	0 ± 0.023	99.327	99.643	0.993	96.88	0 ± 0.016
Stable Angina (2)	93.528	96.689	0.931	94.46	0 ± 0.018	90.29	95.002	0.902	95.07	0 ± 0.037	84.987	92.106	0.849	95.76	0 ± 0.039
Unstable Angina (1)	99.723	99.841	0.997	94.86	0 ± 0.027	99.525	99.742	0.995	93.96	0 ± 0.017	98.547	99.251	0.985	94	0 ± 0.021
Valvular heart disease (6)	97.824	98.885	0.975	94.49	0 ± 0.025	98.135	99.041	0.98	94.157	0 ± 0.029	96.426	98.174	0.964	95.117	0 ± 0.034
Overall Average (231)	97.362	98.647	0.971	94.792	0 ± 0.019	95.686	97.779	0.956	95.091	0 ± 0.027	95.19	97.515	0.951	95.266	0 ± 0.027

Chapter 3

Hardware Validation for IR and CS using AAMI Database [28], [34]

This chapter explains the first experiment carried out while working on the concept of Irregular Sampling and Compressive Sensing. Before this we give a brief introduction on the two. The reference book quoted is [35]. Its a fascinating read.

3.1 Irregular Sampling

The following Lemma and Corollary from the book [35] is applicable to the experiments carried out.

Lemma of the theorem for 1-D Signals:If the nonuniform samples $\{t_n\}$ satisfy the Nyquist rate on the average, it can uniquely represent a band-limited signal deterministicorrandom if the samples are not the zero-crossings of a bandlimited signal of the same bandwidth. The set $\{t_n\}$ is then called a sampling set Proof by Farokh Marvasti: Suppose there is one solution to a set of nonuniform samples at instances $\{t_n\}$ and assume that it is possible to interpolate a bandlimited function of the same bandwidth at the zero-crossings $\{t_n\}$. Now, if we add this interpolated function to the first solution, we get another bandlimited function of thesamebandwidth having the same nonuniform samples; i.e. the solution is not unique.

Corollary 1 If the average sampling rate is higher than the Nyquist rate, irrespective of the set $\{t_n\}$, there is always a unique solution Proof by Farokh Marvasti: The average density of zero-crossings realzeros of a signal bandlimited to W is always less than or at most equal to the Nyquist rate 2W for deterministic and random signals. The sampling positions therefore cannot be the zero-crossings of a signal bandlimited to W. From Lemma 1, we conclude that the samples are a sampling set.

Theorem 1 (Lagrange interpolation theorem) Given $n+1$ distinct (real or complex) points, $z_0, z_1, \cdots, z_n$ and $n+1$ (real or complex) values, $w_0, w_1, \cdots, w_n$, there exists a unique polynomial, $p_n(z)$ P_n for which $p_n(z_i) = w_i, i = 0, \cdots, n$.

The lemma and corollary from Chapter 4 while the theorem from Chapter 3 are quoted verbatim from the book Nonuniform Sampling: Theory and Practice: Theory and Practice, edited by Farokh Marvasti, 2001, Springer.

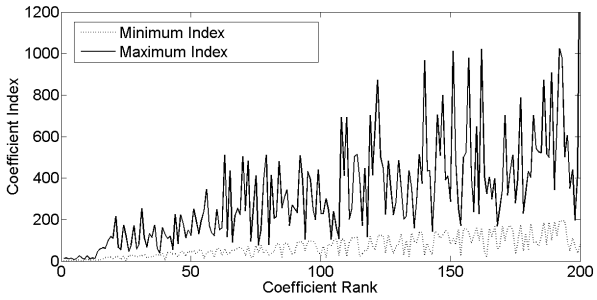


Figure 3.1: Range of coefficient indices occupying ranks 1–200.

3.2 Compressive Sensing [36]

Compressive sensing addresses the method of directly acquiring a compressed signal representation without going through the intermediate stage of acquiring N samples. Consider a general linear measurement process that computes $M < N$ inner products between x and a collection of vectors $\{\varphi_j\}_{j=1}^{M}$ as in $y_j = \hbar x, \varphi_j \mathbf{i}$.. Arrange the measurements y_j in an M 1 vector y and the measurement vectors φ_j^T as rows in an M xN matrix Φ. Then, y can be written as $y = \Phi X = \Phi\Psi s = \Theta s$ where $\Theta = \Phi\Psi$ is an M xN matrix. The measurement process is not adaptive, meaning that Φ is fixed and does not depend on the signal x. The problem consists of designing a) a stable measurement matrix Φ such that the salient information in any K-sparse or compressible signal is not damaged by the dimensionality reduction from $x\ R^N$ to $y\ R^M$ and b) a reconstruction algorithm to recover x from only $M \approx K$ mesurements of y.

The Compressive Sensing paragraph is quoted as given in the lecture notes of Richard G. Baraniuk.

3.3 Reconstruction Algorithm

Given an initial under sampled signal x_d, one solves for the wavelet transform of original signal $\hat{x}$. Once solved for $\hat{x}$, one can take its inverse wavelet transform $\Psi\hat{x}$ to recover the desired estimated signal x_s. To do this, the OMP algorithm is modified to target it for standard ECG signals, This is called Targetted OMP (TOMP) [37]. First one takes discrete wavelet transform using Daubechies 'DB4' basis, arrange the coefficients in the decreasing order of magnitude, and rank them. One can notice that the coefficient indices that occupy a certain rank for the signals under consideration lie within a certain range. This observation is depicted in Fig. 3.1.

In view of Fig.3.1, one targets the OMP in the following manner. Originally, one selects a new index from the entire search space of indices. In contrast, on should restrict the search space according to the rank of the said index. Specifically, divide the coefficient ranks into certain stages, and use different search space for each stage. However, the stage is dictated also by the cumulative energy so far recovered. In Fig.3.2, TOMP algorithm with two stages is descirbed. Each coefficient index is added to the support, and the coefficient value is reconstructed exactly as in OMP. However, the stage r is parameterized by three numbers: C_r indicates the maximum index location to be searched, P_r the maximum cumulative energy to reach to go to the next stage, and I_r the maximum

number of iterations to complete before going to next stage. One moves on to stage $r+1$ if either the energy reaches P_r, or the number of iterations reaches I_r. Over several runs, we settled for a five stage implementation with parameters: $C_1 = 100$, $C_2 = 200$, $C_3 = 500$, $C_4 = 1000$, $C_5 = 1500$, $P_1 =$
95%, $P_2 = 97\%$, $P_3 = 98\%$, $P_4 = 99\%$, $P_5 = 100\%$, $I_1 = 80$, $I_2 = 80$, $I_3 = 90$, $I_4 = 40$, $I_5 = 40$.

3.4 Hardware Implementation

The above sections were added to give a feel for the theoretical background and the simulation studies which were done on the AAMI signals. This section describes the hardware validation of the CS technique. Prior to hardware validation, the four AAMI signals were studied, AAMI 3c was found to have the least sparsest representation using DWT. In each signal the best pattern out of a 100 was found and the block which gives the worst reconstruction values were identified. Then using two ARM Mbed kits in handshake mode, the signal was fed from DAC of one kit as a transmitter to the ADC of the other as a reciever. The signal block was continously transmitted at the rate of 720 Hz. However the reciever would accept the signal only at the 4^{th} iteration; this was done to avoid the transients, if any.

Before transmitting the AAMI signals were scaled and shifted, firstly because the ADC is unipolar and secondly to better match the full scale range of the ADC. The operations involved only the use of scalars. Furthermore since the signal was sampled at 720 Hz. Using Internal Timers the signal was sent to the DAC and the frequency was measured using the oscilloscope.

Figure 3.4 lists the values of the performance metrics which were described in previous chapter. Figure 3.5 lists the same after passing through a 16-tap FIR LPF. Based on the results shown in the two figures, its clear that slight changes in the amplitude, phase affects the R^2 values. Moreover another observation is that the best patterns belong to the AAMI 3c always gives better results than others.

In the next chapter we address the issue of selection of the mother wavelet and the empirical study done on it.

Input: Measurement Matrix $A = S_d \Psi$, Measurement Vector $= x_d$
and Sparsity K.
Output: Set of indices $S \subset \{1, ..., n\}$ of non-zero coeff.s in $\hat{x}$
Initialize: $S = \varnothing$, $res = x_d$, $FLAG = 0$, No. of Iterations : $i = 0$
1. A_0 is constructed by selecting the C_1 columns of A.
  while $FLAG == 0$
    $u = A_0^0 * res$
    $j_0 =$ index of the largest magnitude coefficient of u
    $S = S \cup j_0 \forall j_0 \notin S$
    Compute $\hat{x}$, the minimizer of $\|A_0 \hat{x} - x_d\|_2$ subject to
    $support(\hat{x}) = S$
    $res = x_d - A_0 \hat{x}$
    if $energy(x) \geq P_1 \%\ energy(x_d) \| i \geq I_1$
      $FLAG = 1$
  end while
2. A_2 is constructed by selecting the C_2 columns of A.
  while $FLAG == 1$
    $u = A_2^0 * res$
    $j_0 =$ index of the largest magnitude coefficient of u
    $S = S \cup j_0 \forall j_0 \notin S$
    Compute $\hat{x}$, the minimizer of $\|A_2 \hat{x} - x_d\|_2$ subject to
    $support(\hat{x}) = S$
    $res = x_d - A_2 \hat{x}$
    if $energy(x) \geq P_2 \%\ energy(x_d) \| i \geq I_2$
      $FLAG = 2$
  end while
Return $I, \hat{x}$

Figure 3.2: Targetted OMP (TOMP) algorithm with two stages.

```
After saving the AAMI files saw their min, max values
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', min(y1), min(y2), min(y3), min(y4));
1=-0.033691406250000, 2=-0.026367187500000, 3=-0.045410156250000, 4= -0.021484375000000
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', max(y1), max(y2), max(y3), max(y4));
1=0.038574218750000, 2=0.065917968750000, 3=0.032714843750000, 4= 0.044921875000000

Scaling by 22.2608 to make max value near 1.0
>> y5 = y1*22.2608; y6=y2*22.2608;y7=y3*22.2608;y8=y4*22.2608;
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', min(y5), min(y6), min(y7), min(y8));
1=-0.749997656250000, 2=-0.586954687500000, 3=-1.010866406250000, 4= -0.478259375000000
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', max(y5), max(y6), max(y7), max(y8));
1=0.858692968750000, 2=1.467386718750000, 3=0.728258593750000, 4= 0.999996875000000

adding dc shift
>> y9=y5+1.010866406250000;y10=y6+1.010866406250000;y11=y7+1.010866406250000;y12=y8+1.010866406250000;
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', min(9), min(y10), min(y11), min(y12));
1=9.000000000000000, 2=0.423911718750000, 3=0.000000000000000, 4= 0.532607031250000
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', max(y9), max(y10), max(y11), max(y12));
1=1.869559375000000, 2=2.478253125000000, 3=1.739125000000000, 4= 2.010863281250000

downsscaling
>> y13=y9/2.478253125000000;y14=y10/2.478253125000000;y15=y11/2.478253125000000;y16=y12/2.478253125000000;
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', min(y13), min(y14), min(y15), min(y16));
1=0.105263157894737, 2=0.171052631578947, 3=0.000000000000000, 4= 0.214912280701754
>> fprintf('1=%3.15f, 2=%3.15f, 3=%3.15f, 4= %3.15f \n', max(y13), max(y14), max(y15), max(y16));
1=0.754385964912281, 2=1.000000000000000, 3=0.701754385964912, 4= 0.811403508771930
```

Figure 3.3: Scalar Operations performed on the AAMI signals for ADC support

dwn2	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	86.9337	91.5434	99.1352	99.6281	1.0017	0.9989	98.584	94.3115	-0.001	0.0005	0.0094	0.0061
AAMI3b	90.0555	91.1328	99.4881	99.6887	0.9999	1.0026	98.3398	97.3145	-0.0001	-0.0015	0.0075	0.0066
AAMI3c	87.6113	87.9541	99.2818	99.3887	0.9933	0.9939	98.291	98.0713	0.0031	0.0029	0.0161	0.0199
AAMI3d	91.4836	92.7154	99.7082	99.7143	1.0071	1.0014	96.3623	96.0205	-0.0038	-0.0008	0.0043	0.0066
dwn3	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	85.5707	85.4818	99.0555	98.9389	0.9936	0.9975	97.7295	97.9248	0.0035	0.0012	0.0098	0.0184
AAMI3b	83.0088	86.145	99.335	99.2196	0.9921	1.0006	98.291	98.7861	0.0095	-0.0047	0.0086	0.0093
AAMI3c	75.4783	74.6887	96.5227	96.9863	0.9991	1.0183	98.0557	97.998	-0.0004	-0.006	0.0214	0.0213
AAMI3d	90.2185	91.0823	99.5045	99.5897	1.0019	1.0024	96.7773	96.0938	-0.0011	-0.0014	0.0039	0.003
dwn4	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	86.4714	61.7446	99.0965	93.7685	1.0016	0.9828	96.8994	99.0479	-0.0011	0.0094	0.0095	0.0258
AAMI3b	86.9311	86.8284	99.1476	99.1317	1.0012	1.0009	97.3145	97.583	-0.0006	-0.0004	0.0054	0.0055
AAMI3c	77.7244	78.1476	97.6627	97.6541	1.0001	0.993	97.0703	97.168	-0.0044	0.0032	0.0185	0.0184
AAMI3d	85.7478	89.7831	99.0896	99.519	1.0076	1.0055	96.8506	95.9717	-0.0042	-0.0028	0.0124	0.009
dwn5	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	73.869	46.6571	96.9303	85.1982	0.9984	1.0069	96.8262	98.3154	0.0052	-0.0059	0.0181	0.038
AAMI3b	74.5113	90.0165	97.39	99.488	0.9923	0.9977	98.1201	95.459	0.0036	0.0012	0.0175	0.0076
AAMI3c	67.8381	66.5798	95.183	94.6155	1.0069	1.0025	96.7773	96.9971	-0.0039	-0.0017	0.0273	0.0286
AAMI3d	88.4362	88.5821	99.3861	99.4857	1.0066	1.0067	95.1172	95.3857	-0.0037	-0.0037	0.01	0.0099
dwn6	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	47.1495	75.6835	86.2772	96.9943	1.0115	1.0087	97.0215	96.6804	-0.0078	-0.0088	0.0367	0.0172
AAMI3b	10.2682	57.758	88.3154	91.0448	1.0103	1.0049	99.4629	97.3633	-0.0037	-0.0038	0.0673	0.0315
AAMI3c	44.9896	45.1479	84.3452	84.9143	0.9949	0.9966	97.3389	97.29	0.0005	-0.0004	0.0469	0.0467
AAMI3d	31.6089	34.6825	98.32	98.8467	1.0027	1.0048	96.0898	95.5566	-0.0016	-0.0027	0.0169	0.0139

Figure 3.4: Hardware Reconstruction Results on the AAMI signals

dwn2	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	86.5337	91.5434	99.1352	99.6281	1.0017	0.9989	98.584	94.3115	0	0	0	0
AAMI3b	90.8555	91.1328	99.4981	99.6887	0.9999	1.0026	98.2398	97.3145	0	0	0	0
AAMI3c	87.6113	87.9941	99.2818	99.3887	0.9983	0.9939	98.291	98.0713	0	0	0	0
AAMI3d	91.4636	92.7154	99.7082	99.7143	1.0071	1.0014	96.3623	96.0205	0	0	0	0
dwn3	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	87.1473	98.9285	99.1528	99.5496	0.9999	0.9987	98.3154	94.9463	0	0	0.0001	0.0001
AAMI3b	89.3386	98.2377	99.4561	99.5571	0.9961	1.004	98.5187	98.0469	0	0	0.0001	0.0001
AAMI3c	86.0168	86.5881	99.0583	99.0845	0.9949	0.9978	97.6874	97.4619	0	0	0.0001	0.0001
AAMI3d	92.0462	92.917	99.722	99.73	1.0059	1.0016	96.2646	96.2891	0	0	0.0001	0.0001
dwn4	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	86.4988	85.7743	99.1151	99.0477	0.9982	0.9963	97.876	98.1201	0	0	0.0002	0.0002
AAMI3b	87.5288	88.7734	99.4612	99.467	0.9922	1.0051	98.4131	98.504	0.0001	-0.0001	0.0001	0.0001
AAMI3c	79.822	79.8927	97.9256	97.954	0.9984	1.0017	97.9492	97.7851	0	0	0.0003	0.0003
AAMI3d	91.3876	92.1378	99.6556	99.6812	1.0049	1.0024	96.167	95.5078	-0.0001	0	0.0002	0.0002
dwn5	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	94.5726	78.4675	98.9132	97.7526	0.9795	0.9667	97.1524	98.0713	0.0001	0.0001	0.0002	0.0004
AAMI3b	86.6286	89.1102	99.3241	99.3818	0.9826	1.0046	96.8586	96.4111	0.0001	0	0.0002	0.0002
AAMI3c	80.5813	81.275	98.2739	98.3876	1.0153	1.0072	96.167	96.1426	-0.0001	-0.0001	0.0004	0.0004
AAMI3d	87.373	89.5483	99.1924	99.4516	0.9984	1.0162	95.4182	95.3369	0	0	0.0002	0.0002
dwn6	RSQR		CORR		REGR		BLAL		Mean€		STD€	
Block of	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2	pat1	pat2
AAMI3a	85.8593	85.8782	98.981	98.9751	1.0004	0.9988	97.8516	97.1436	0	0	0.0007	0.0007
AAMI3b	87.982	89.5554	99.2526	99.497	0.9963	1.0055	97.9746	97.1191	-0.0001	0.0002	0.0006	0.0005
AAMI3c	84.1783	85.0344	98.8345	98.8583	0.99	0.9973	96.6309	96.3135	-0.0003	-0.0001	0.0009	0.0009
AAMI3d	92.1832	92.7843	99.6974	99.7152	1.0054	0.9999	95.6543	96.2158	0.0002	0	0.0006	0.0006

Figure 3.5: Hardware Reconstruction Results on the AAMI signals after Filtering

Chapter 4

Empirical Study on the sparsest representation of ECG

While performing the experiments on the AAMI signals one question that came to mind was on the selection of the basis which will give sparsest representation. Since we had two databases of different frequencies, the idea to find the best possible mother wavelet to represent the ECG signals sparsely was hit upon. The motivation, procedure and results of the same are included in this chapter.

4.1 Motivation

- Compressive Sensing (CS) provides an encouraging solution towards efficient compression and low rate transmission.
- Idea is we sample ECG compressively and then reconstruct it without loss in diagnostic value.
- However CS based methods requires the signal to be sparse when represented in some basis. Lack of clear understanding on why certain wavelets are being used for CS and irregular Sampling.
- Use of study results to achieve very good compression with an aim to reduce power consumption at the time of capturing as well as at transmission time.
- Enabling the use of the concept of irregular sampling (IR) and recovery of signal using Compressive Sensing (CS) which are relatively new emerging fields.
- Using the best possible mother wavelet to improve existing results.
- Improvement is in terms of denoising, compression, sparse/ minimal representation.

4.2 Experiment Details

- 228 records (out of 546) from PTBDB database finished.
- All possible consecutive segments of 4096 samples were considered per lead. Consecutive segments have overlap of 256 samples. This amounts to 85935 segments available for analysis.

- Record to patient (disease) mapping Pending will be done shortly.
- Wavelets chosen:
  - Daubechies family. (10)
  - Symlets.(7)
  - Biorthogonal wavelets.(15)
  - Reverse biorthogonal wavelets.(15)
  - Discrete Meyer wavelet

4.3 Flowchart

Figure 4.1 gives the flowchart of the experiment carried out.

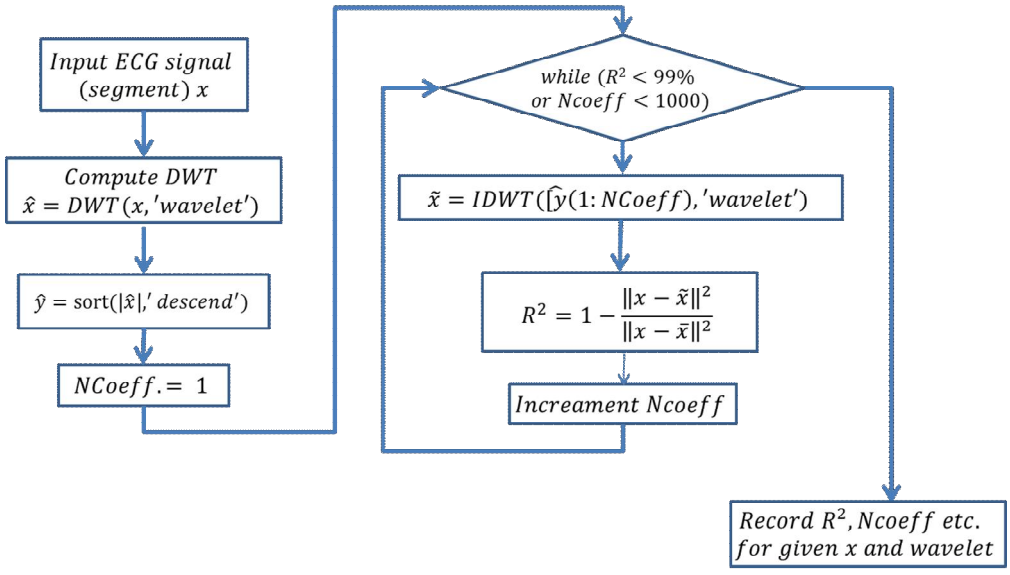


Figure 4.1: Flowchart used to study and find the wavelet giving the sparsest representation for ECG signals

4.4 Results

Firstly the best performing wavelets in each family is shown in 4.4. Figure 4.2 shows the wavelets according to their ranking over each lead and overall on an average! According to the graph shown in fig. 4.2 Symlet 4 is the best performing wavelet which has the sparsest representation among all the other wavelets.

4.5 Conclusion

- Symlet family gives better compression.

- Out of the top 5 wavelets, all belong to symlets
- An interesting phenomena is that overall except for lead I sym6 is better than sym4.
- Overall v1 to v6 and vx gives better compression

Thus such a result will indicate which leads to capture on a priority basis and why.

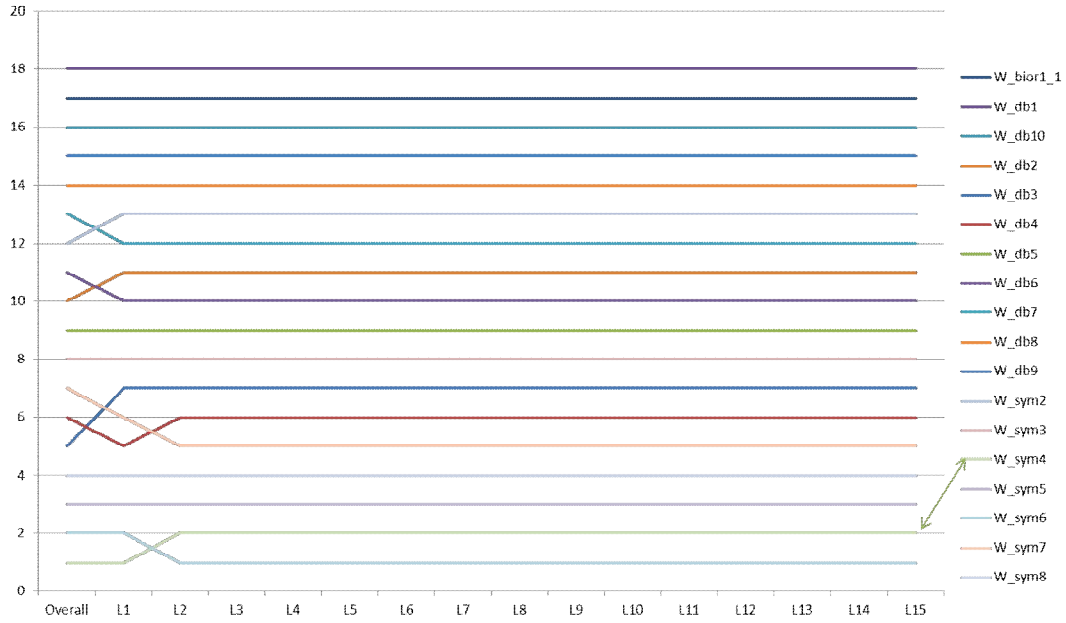


Figure 4.2: Wavelet ranking for all the leads and per lead

In the next chapter we describe the circuit built for the one-lead data acquisition system.

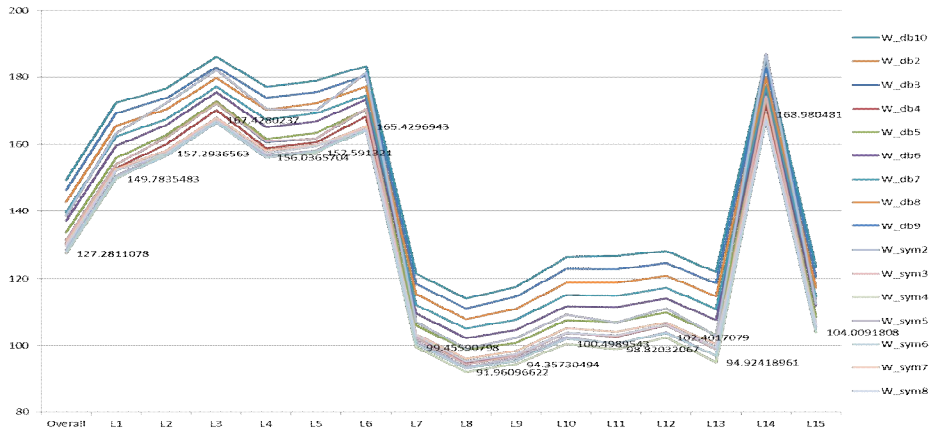


Figure 4.3: Top ten wavelets for each lead as well as overall with respect to the number of coefficients required to represnt it.

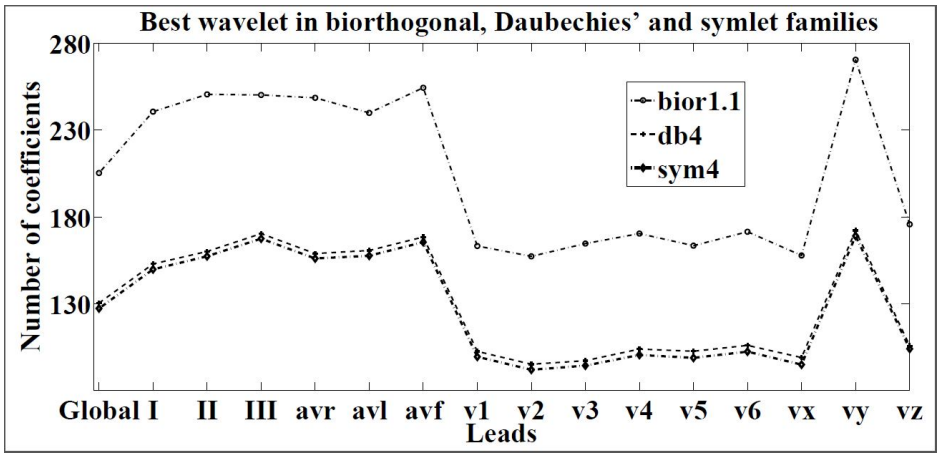


Figure 4.4: Best performing wavelet from each family. Bi-orthogonal, Daubechies' and symlet families.

Chapter 5

One Lead ECG Data Acquisition System

While trying to capture live ECG using a bandwidth of around 100 Hz, the PLI was too high! Thus based on the study in chapter 2, a new Data Acquisition System was designed.

5.1 Signal Characteristics

The ECG signal is a bio-potential signal whose amplitude is in the range of 1μV to 1 mV, while the frequency range is from 0.05 to 125 Hz. However the study done in chapter 2 shows that the major frequency content in the signal is around 20 Hz.

5.2 Circuit Background

The data acquisition system for any bio-potential signal will consist of amplification, common signal rejection and bandlimiting. Since these are bio-potential signals, the first component in general is always the instrumentation amplifier, this is followed by a low pass filter generally of 4^{th} order and then a programmable gain amplifier. The reason for having a second stage of gain amplifier is first to prevent the saturation of the Instrumentation Amplifier and second to provide for improving the signal amplitude before feeding to the ADC.

The main attention in the work carried out was to develop a low cost portable ECG Data Acquisition System ASIC. The first step in it was to develop a discrete components based circuit, study the signal, circuit behaviour and signal-system interaction. While developing such a discrete components based system, the idea of creating a low cost board which tries to minimize the number of components and cost was explored. One idea explored was to make the system design modular.

5.3 First Lead 1 Data Acquisition Circuit

The schematic of the first circuit created is shown in Fig 5.1. The signal conditioning circuit (SCC) used is shown in Fig. 5.2. The output of the SCC is fed to the Mic-in port of the PC using a TRS

connector. This system configuration tries to make use of the circuitry which is already built on the sound card, namely a 16-bit dual SAR ADC, sampled at 8 KHz, a coupling capacitor and so on. There exist a lot of SCCs which make try to make use of the Mic-in port. However the main purpose of the Mic-in port is audio, hence the optimum range is not the range we want. A frequency analysis showed that the sound card can take in V_{pp} = 100 mV when configured as mic-in and V_{pp} = 1 V if configured as a line-in port. While trying to find the frequency response of the system, a notch in the frequency response around 50 Hz was observed. Also as these signals are not audio signals, there is a 4 dB attenuation for ECG signals in the bandwidth of interest. In Fig. 5.3 the comparison between a filtered wave captured using the PC's ADC is shown to compare with that of an ECG signal from the PTB database. Figure 5.4 shows the same ECG signal which was captured at different time, the frequency content was highlighted to show that the results from the circuit are repeatable and reproducible.

Figure 5.5 shows the frequency response of the system when configured as Mic-in port. The speech range is from 300 - 4KHz. As can be seen from the fig. the response also includes a notch at 50 Hz. However the cause for concern was at low frequencies as seen in Fig 5.6. Since ECG is a low frequency signal and since the response of the system showed attenuation in the lower range. Thus further filtering in digital domain is required which compensates for the filtering effect introduced by the system, furthermore since we cant go below 8 KHz, excess power is wasted in terms of sampling.

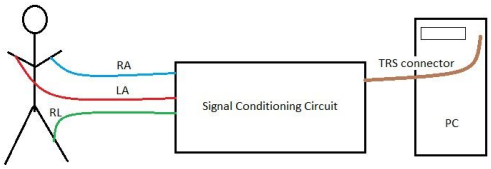


Figure 5.1: Schematic representation of 1-Lead Data Acquisition System

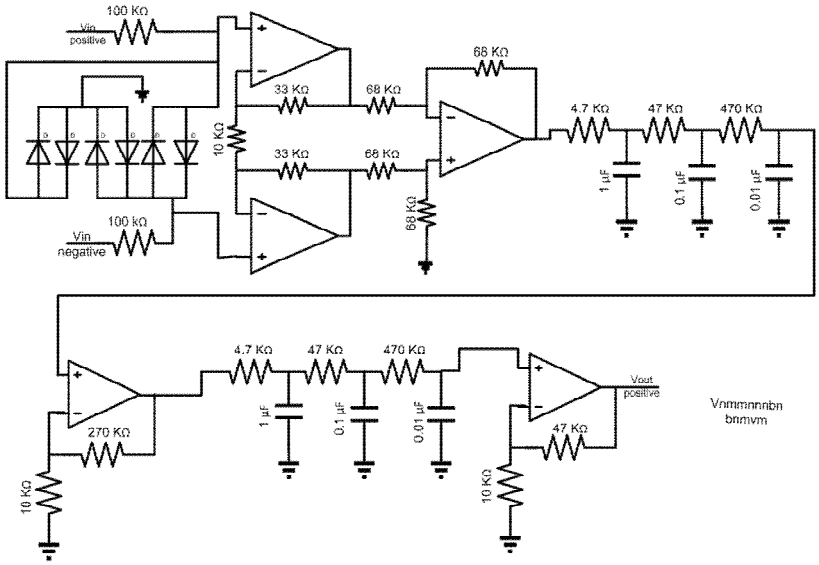


Figure 5.2: Schematic representation of 1-Lead Data Acquisition System

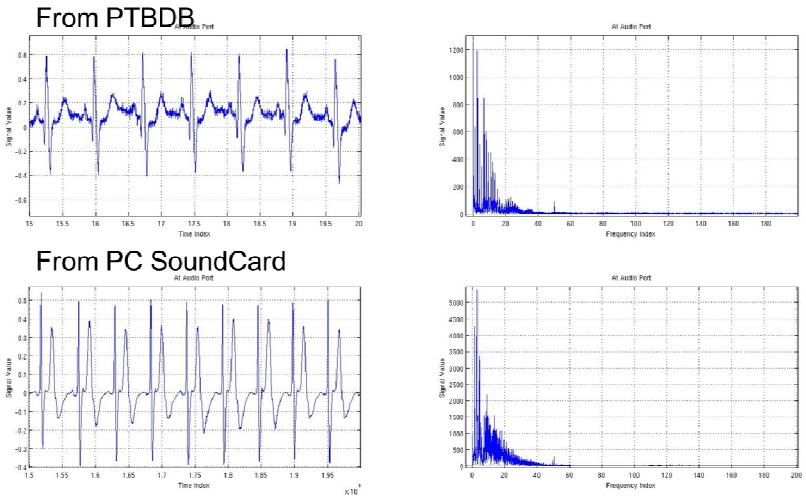


Figure 5.3: Time and Frequency domain comparison of the filtered signal captured using the Mic-in port with that of an ECG signal from the PTB database.

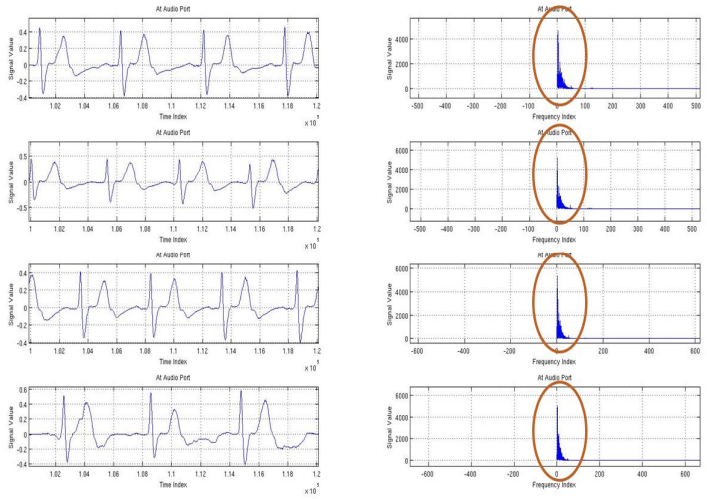


Figure 5.4: Schematic representation of 1-Lead Data Acquisition System

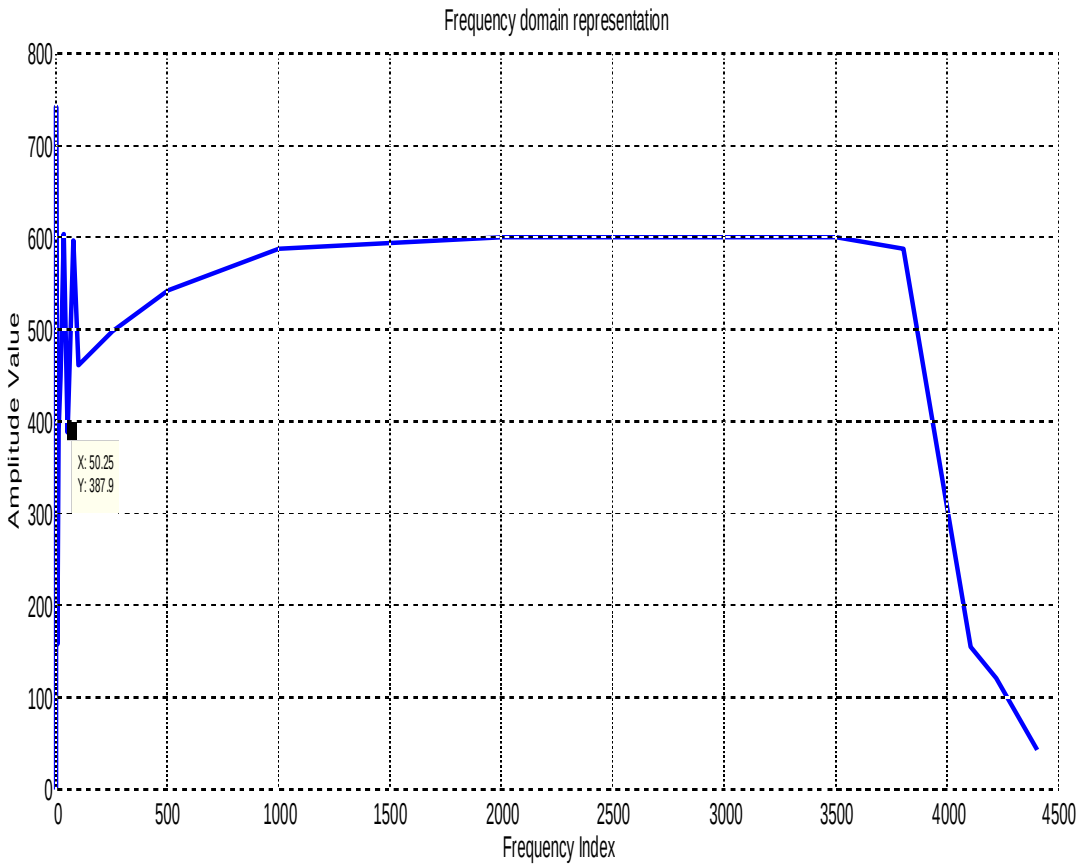


Figure 5.5: Frequency Response of the sound card's TRS port when configured as Mic-in

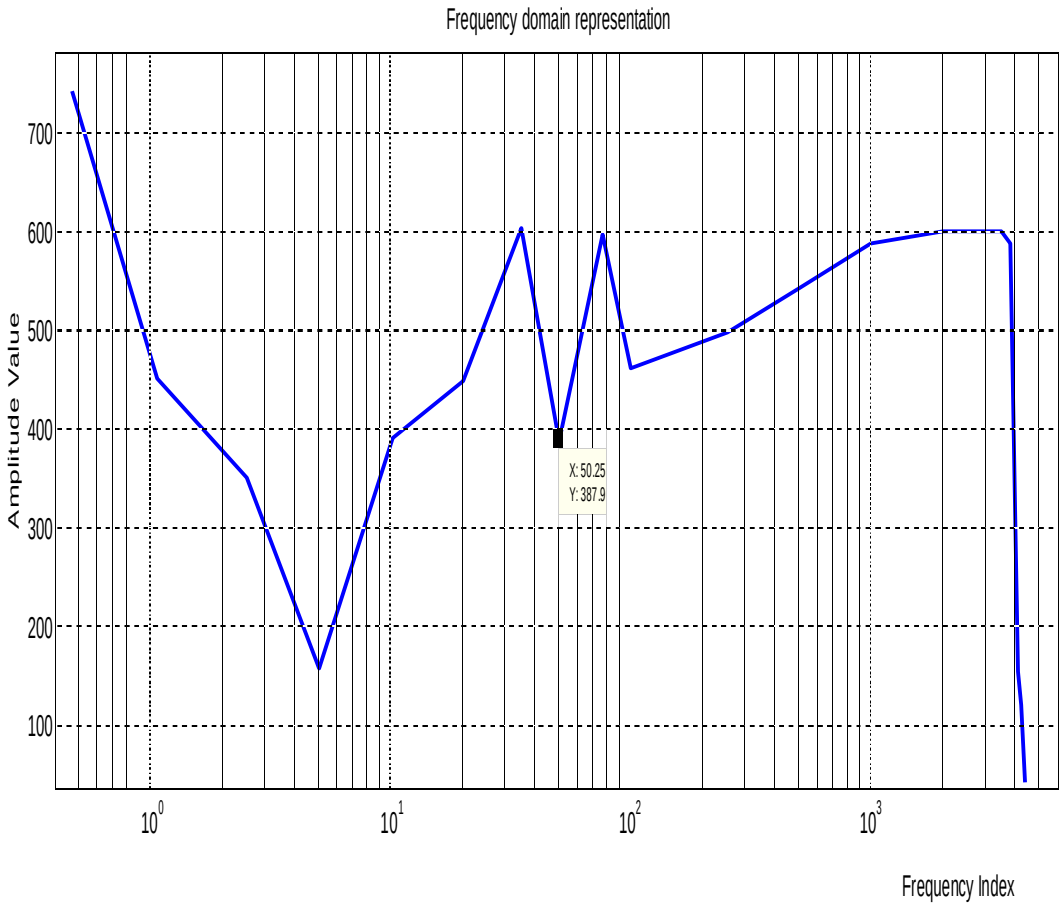
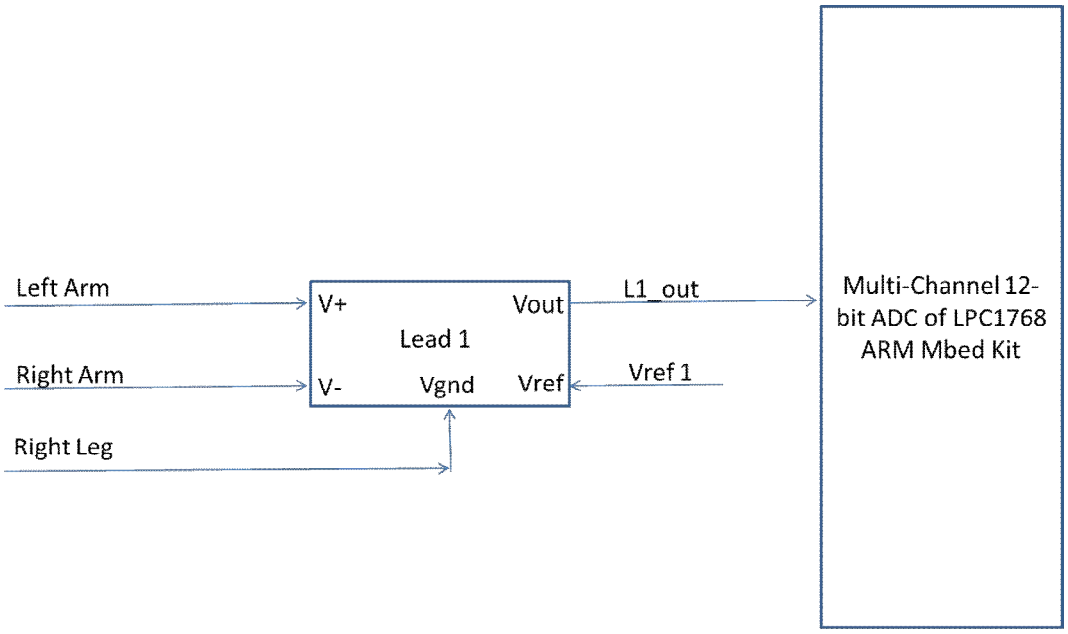


Figure 5.6: Frequency Response of the sound card's TRS port when configured as Mic-in in semi-log scale.

5.4 Second Lead 1 Data Acquisition Circuit

Thus to avoid the complications of designing a matching filter and unable to recoup the loss caused by oversampling. A µC based solution was explored. Because of this the amount of digital filtering required is only a smoothening filter. The schematic representation of the system is shown in Fig. 5.7. The circuit level description of the SCC is shown in Fig. 5.8. Shown in Fig. 5.9 are the Lead 1 ECG waves which were simultaneously sampled, one at rate of 1000 Hz and the other such that the average sampling rate is 250 Hz. We can see that the two ECG waves overlap. In the figure we took two iterations.



1 Lead Data Acquisition Circuit

Figure 5.7: Schematic representation of 1-Lead Data Acquisition System

Thus we have using the board have been able to capture the ECG signal at 50 Hz as shown in Fig. ?? as well as prove the concepts of Irregular Sampling and Compressive Sensing. In the next chapter the concept is extended to 3-lead data acquisition systems.

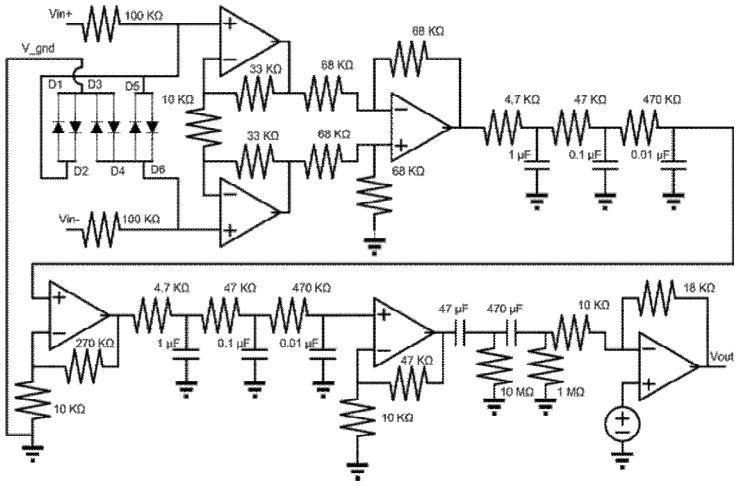


Figure 5.8: Circuit representation of the SCC of 1-Lead Data Acquisition System

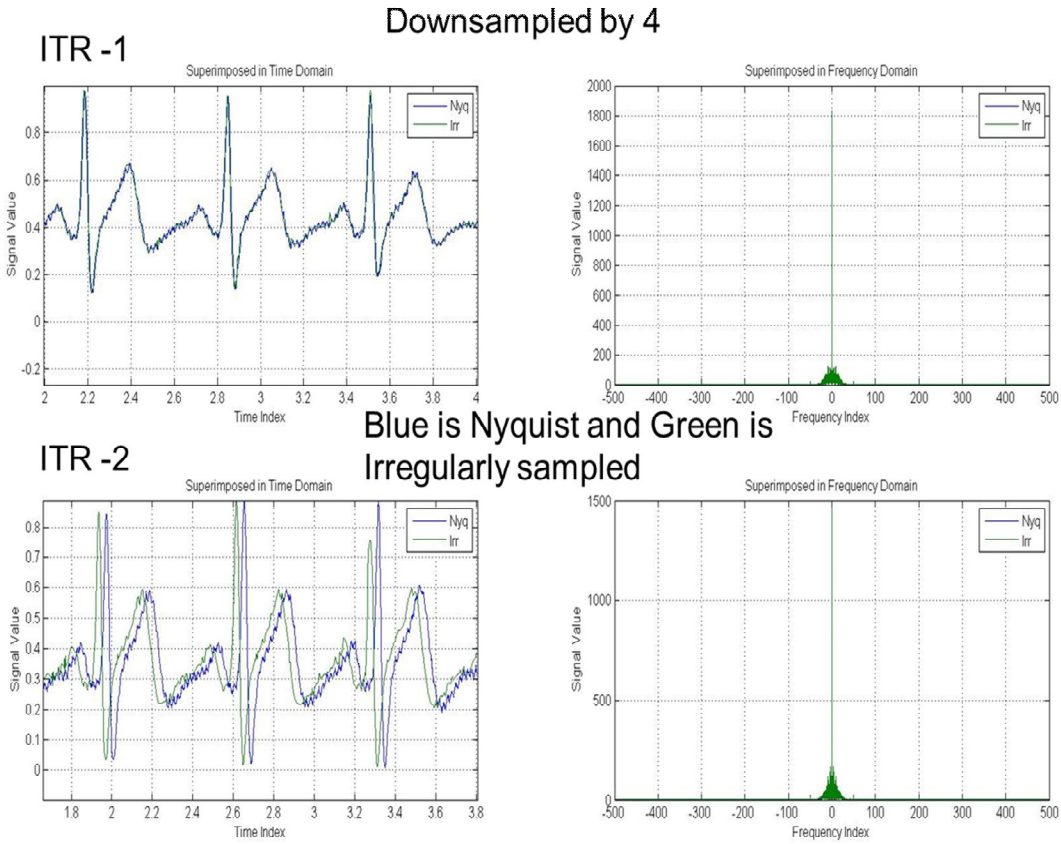


Figure 5.9: Simultaneous Sampling of a live ECG signal; oversampled at 1000 Hz, the other irregularly sampled at 250 Hz.

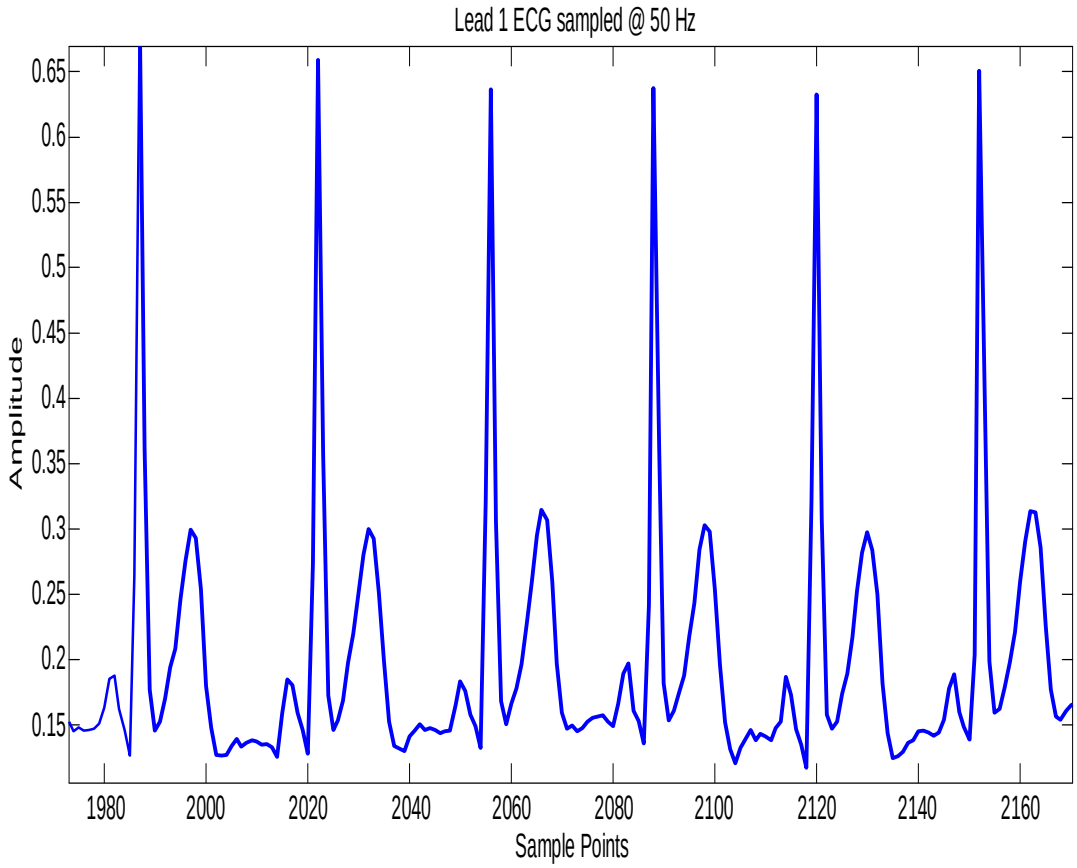


Figure 5.10: Sampling of a live ECG signal sampled at 50 Hz

Chapter 6

Three Lead ECG Data Acquisition System

This is basically an extension work, the main focus of this work was to try and capture three ECG signals simultaneously using three SCCs and one multichannel ADC.

6.1 Schematic Diagram

Figure 6.1 gives the schematic representation of the circuit made to capture the 3 ECG leads. All three ECG boards were shorted and the power was given through a split supply. The feedback resistors of the circuits had to be changed which demonstrated the need for programmable gain. The signal conditioning circuit is shown in Fig. 6.2

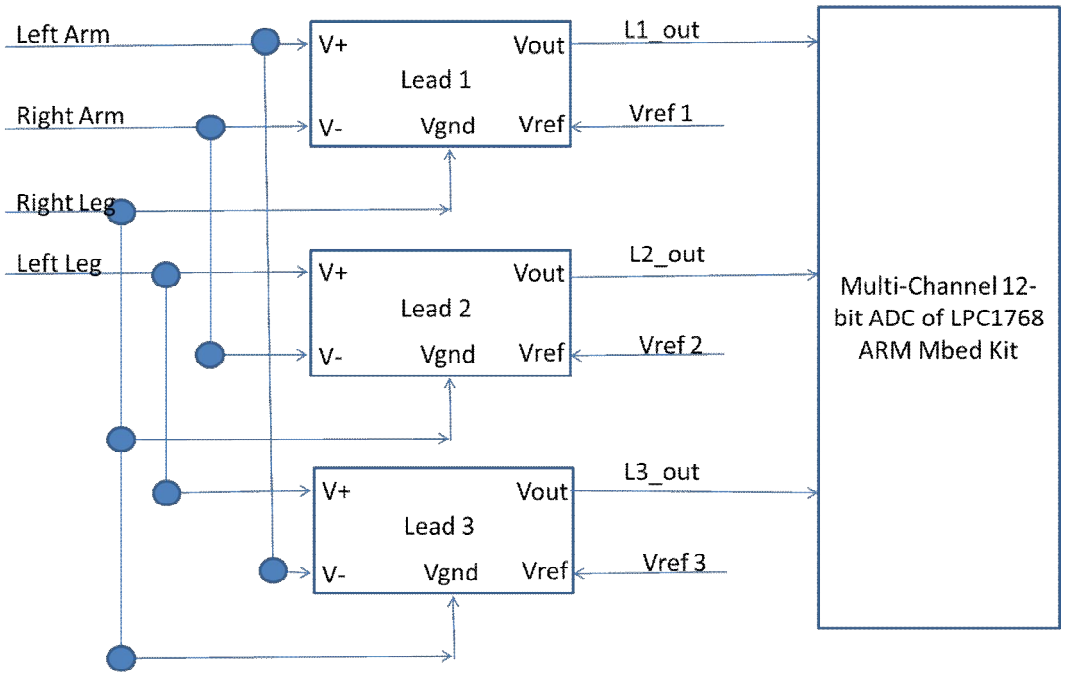
6.2 3-Lead Data Capturing

The 3-Lead ECG data was captured in different ways, firstly tried to capture using three different ADCs, however synchronization issue posed a problem. Later we went with utilizing the multichannel capability of the ADC, with this using software programming control and then using 74LS163 and 74HS139 synchronous counter and decoder respectively we were able to capture the ECG signals simultaneously.

We also were able to prove the concept of Irregular Sampling and Compressive Sensing for three signals simultaneously.

6.3 Results

We captured the data for six subjects. Shown here are the reconstruction results for downsampling by 6. Both the nyquist and irregulary sampled signals are shown in Figures 6.3-6.4



3-Lead Data Acquisition System

Figure 6.1: Schematic representation of 3-Lead Data Acquisition System

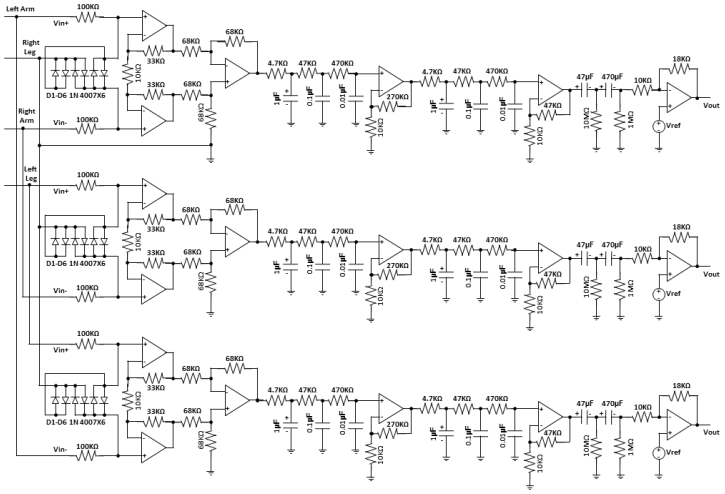


Figure 6.2: Circuit level representation of SCC of 3-Lead Data Acquisition System

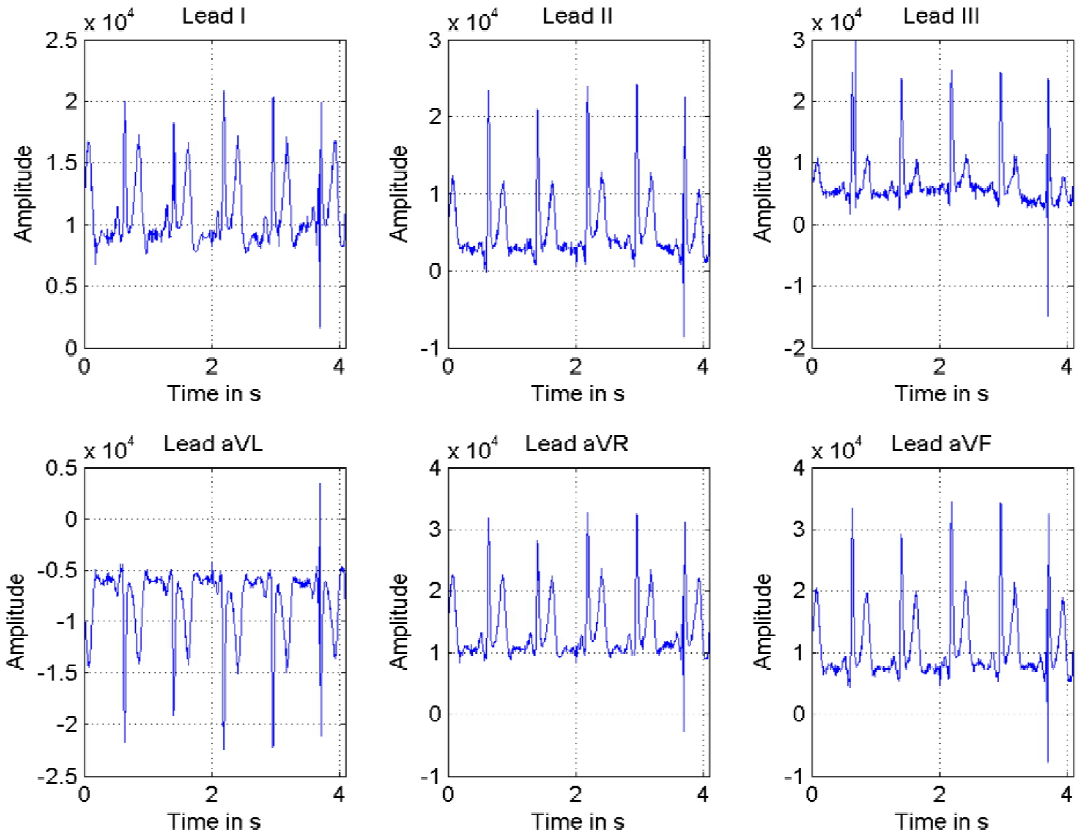


Figure 6.3: Six Lead ECG data without filtering captured using the 3-Lead Data Acquisition System

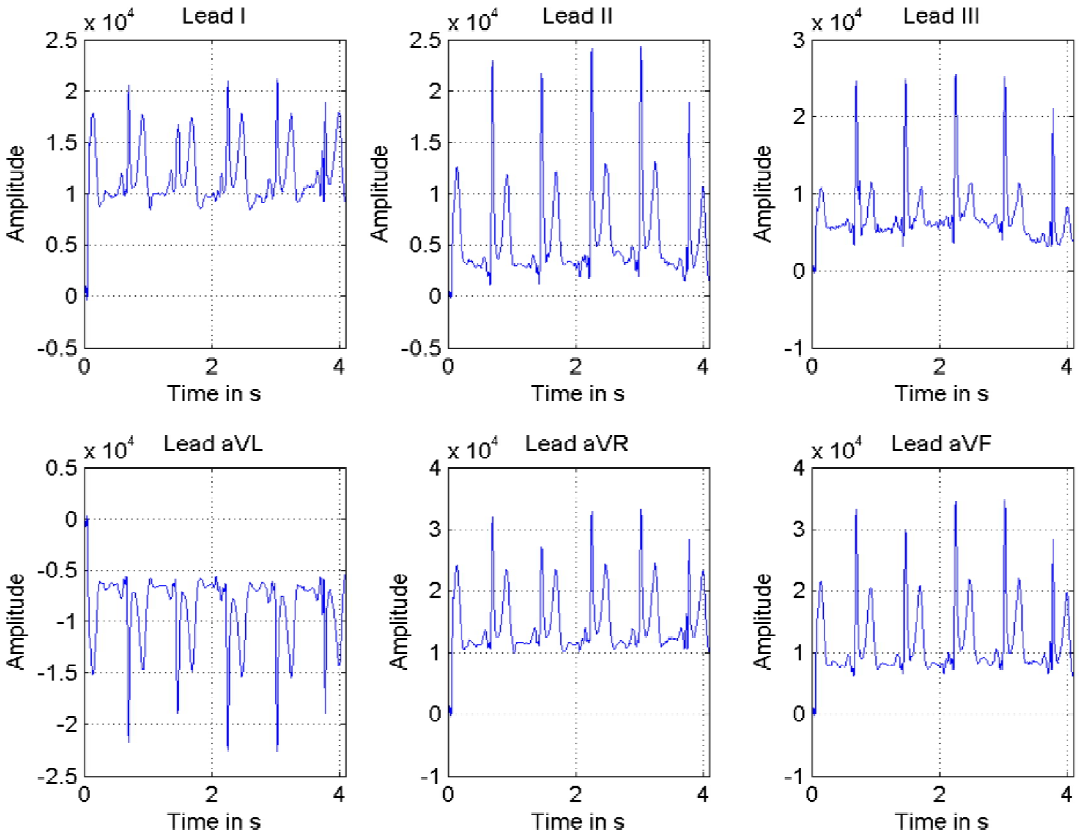


Figure 6.4: Six Lead ECG data without filtering captured using the 3-Lead Data Acquisition System

6.4 Pricing

Below is the price arrived at based on prices listed from internet

- Capacitors: Rs. 3 Nos = 8. Therefore Rs. 24/-
- Resistors: Rs. 0.3 Nos = 24. Therefore Rs. 7.2/-
- ICs: Rs. 10 Nos = 2. Therefore Rs. 20/-
- IC Base: Rs 10 Nos = 2. Therefore Rs. 20/-
- Diodes: Rs 2 Nos = 6. Therefore Rs 12/-
- Price for 1-Lead system components comes to Rs. 83/-
- Price for 3-Lead system components comes to Rs. 250/-
- Price for PCB is fixed at Rs. 300/-

Thus it comes to Rs. 383/- for 1-Lead and Rs. 550/- for 3-Lead. The ARM Mbed kits were free of cost so the price hasnt been included.

In the next chapter the conclusion and future work is presented.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

With the proposed DAB one is able to capture information about six ECG leads simultaneously. The Table 2.1 results validates our proposed design strategy. Hence one can make an affordable ECG signal acquiring DAB for a portable ECG machine as the first stage in detection, diagnosing and warning on CVD to the patient/user. The DAB using this simple topology is possible because the main signal BW is within 20 Hz. The effect of PLI and other high frequency components too is negligible because of reduction in BW. Due to the topology we can use cheap, commonly available electronic components. The circuit itself can be broken into simple stages for debugging. The faulty components can be easily self-replaced, and the cost is light on the pocket. Furthermore component variations studies have been done as well as Gain and BW variation has been done as well, one of them is shown in Fig. 7.1 the other results will be included in the final thesis document.

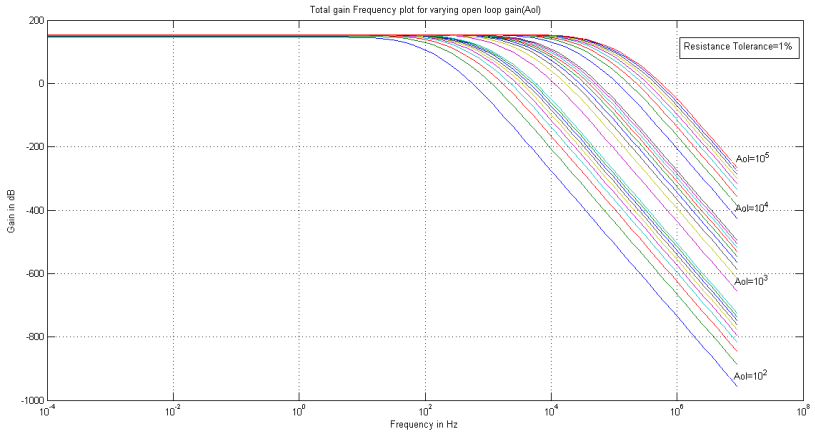


Figure 7.1: Overall Gain variation by using resistors with 1% tolerance.

7.2 Future Work

This work can be carried out in order to develop a robust and rugged portable ECG machine as follows:

- Change the Bandwidth to include upto 100 Hz. This if done can then be used for both ambulatory and full diagnostic purpose.
- Use the existing data as input to the 3 to 12 Lead conversion work on which is going on.
- A design in ASIC level with attention to phase response of each and every cascaded system.
- Ability to record three unipolar ECG lead data simultaneously
- Developing a simple oscilloscope similar to a PC based oscilloscope to allow to record best possible ECG data.
- Control things using click of a button.

Appendices

Appendix A

ECG Background

In this section the medical information and guidelines learnt as part of this project have been added in this thesis report as is with appropriate citation. First the definition of the ECG is given, then the standard procedure to record the ECG signals is given. This is followed by tips with respect to data collection.

An Electrocardiogram (ECG) is a way to measure and diagnose abnormal rhythms of the heart, particularly abnormal rhythms caused by damage to the conductive tissue that carries electrical signals, or abnormal rhythms caused by electrolyte imbalances. Electrocardiography (ECG or EKG from Greek: kardia, meaning heart) is a transthoracic (across the thorax or chest) interpretation of the electrical activity of the heart over a period of time, as detected by electrodes attached to the surface of the skin and recorded by a device external to the body. The recording produced by this noninvasive procedure is termed an electrocardiogram (also ECG or EKG) [15]. Doctors in general and cardiologists in particular give their diagnosis on the basis of the 10-electrode 12-lead ECG setup as shown in Fig A.1 [15].

A.1 Standard ECG Recording

The 10-Electrodes are shown in Table A.1. Table A.2 gives a description of how the 12 leads are extracted from these 10 electrodes. One of the biggest questions people ask regarding a 12-lead ECG is why there are only 10 electrodes. It is important to fully understand what the term lead actually means. A lead is a view of the electrical activity of the heart from a particular angle across the body. Think of a lead as a picture of the heart and the 10 electrodes give you 12 pictures. In other words, a lead is a picture that is captured by a group of electrodes [16].

A.2 Artifact Reduction [16]

A common problem with 12-lead ECG's is that you will get a lot of artifact if your patient is moving around and not fully relaxed. Here are a few guidelines on how to reduce artifact so you can capture a good ECG:

1. Place the patient in a supine or semi-Fowler's position. If the patient cannot tolerate being flat, you can do the ECG in a more upright position.

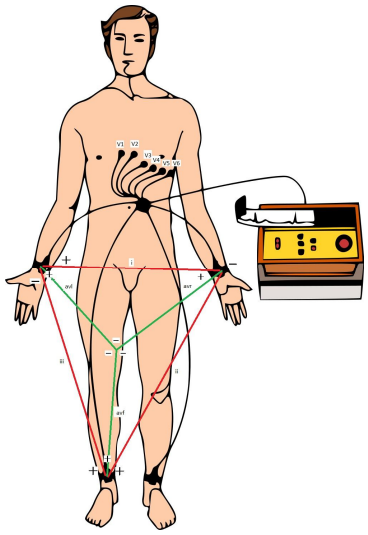


Figure A.1: Standard 10-electrode 12-lead ECG setup

Table A.1: Electrode Labels and Placement of electrode [15]

Electrode label	Electrode Placement
RA	On the right arm, avoiding thick muscle.
LA	In the same location where RA was placed, but on the left arm.
RL	On the right leg, lateral calf muscle.
LL	In the same location where RL was placed, but on the left leg.
V1	In the fourth intercostal space (between ribs 4 and 5) just to the right of the sternum (breastbone).
V2	In the fourth intercostal space (between ribs 4 and 5) just to the left of the sternum.
V3	Between leads V2 and V4.
V4	In the fifth intercostal space (between ribs 5 and 6) in the midclavicular line.
V5	Horizontally even with V4, in the left anterior axillary line.
V6	Horizontally even with V4 and V5 in the midaxillary line.

Table A.2: ECG Leads of the 10-Electrode, 12-Lead Setup[15]. Here $V_w = \frac{1}{3} * (RA + LA + LL)$ is known as the Wilson's Central Terminal

Lead label	Type of lead	Relation with the Electrode
I	Bipolar	$(LA - RA)$
II	Bipolar	$(LL - RA)$
III	Bipolar	$(LL - LA)$
aVR	Bipolar	$RA - \frac{1}{2} * (LA + LL)$
aVL	Bipolar	$LA - \frac{1}{2} * (RA + LL)$
aVF	Bipolar	$LL - \frac{1}{2} * (LA + RA)$
V1	Unipolar	$V1 - V_w$
V2	Unipolar	$V2 - V_w$
V3	Unipolar	$V3 - V_w$
V4	Unipolar	$V4 - V_w$
V5	Unipolar	$V5 - V_w$
V6	Unipolar	$V6 - V_w$

Table A.3: Risk Factors Common to Major NCDs [17], + corresponds to risk factor

Risk Factor	Noncommunicable Disease			
	CVD	Diabetes	Cancer	Respiratory
Smoking/ tobacco	+	+	+	+
Alcohol	+		+	
Nutrition	+	+	+	+
Physical Inactivity	+	+	+	+
Raised BP	+	+	+	
Raised blood Sugar	+	+		
Obesity	+	+	+	+
Blood Lipids	+	+	+	

2. Instruct the patient to place their arms down by their side and to relax their shoulders.
3. Make sure the patient's legs are uncrossed.
4. Remove any electrical devices, such as cell phones, away from the patient as they may interfere with the machine.
5. If you're getting artifact in the limb leads, try having the patient sit on top of their hands.

A.3 Risk Factor Survey

The IDSP survey in India was carried out by the Indian Council of Medical Research (ICMR) with funding from World Bank [17]. In Table A.3 the main factors responsible for CVDs are tabulated and compared with that of other major NCDs.

References

[1] World Health Organization, “Proposed Programme Budget 2008-2009”, 2009

[2] World Health Organization, “World Health Statistics 2012”, WHO Press, World Health Organization, 20 Avenue Appia, 1211 Geneva 27, Switzerland (tel.: +41 22 791 3264; fax: +41 22 791 4857; e-mail: bookorders@who.int). [Online: http://www.who.int/gho/publications/world_health_statistics/2012/en/index.html]

[3] World Health Organization, “Cardiovascular diseases (CVDs)”, Fact sheet N^{0}317, March 2013. [Online: http://www.who.int/mediacentre/factsheets/fs317/en/index.html]

[4] World Health Organization, “World Health Statistics 2013”, WHO Press, World Health Organization, 20 Avenue Appia, 1211 Geneva 27, Switzerland (tel.: +41 22 791 3264; fax: +41 22 791 4857; e-mail: bookorders@who.int). [Online: http://www.who.int/gho/publications/world_health_statistics/2013/en/index.html]

[5] Bang, A., et al, “High Level Expert Group Report on Universal Health Coverage for India”, Dec 2011[Online: http://planningcommission.nic.in/reports/genrep/rep_uhc0812.pdf] Page 31

[6] Technology, Wikipedia [Online: http://en.wikipedia.org/wiki/Technology]

[7] Engineering, Wikipedia [Online: http://en.wikipedia.org/wiki/Engineering]

[8] J. P. P. Gomez, “Telemedicine and Telecardiology Report”. [Online: http://www.slideshare.net/JosePinilla/telemedicine-and-telecardiology-report]

[9] News-Medical.net, “What is Telemedicine?”. [Online: http://www.news-medical.net/health/What-is-Telemedicine.aspx]

[10] News-Medical.net, “What is Telecardiology?”. [Online: http://www.news-medical.net/health/What-is-Telecardiology.aspx]

[11] Ikaro Silva, George B Moody, Leo Celi, “Improving the Quality of ECGs Collected Using Mobile Phones: The PhysioNet/Computing in Cardiology Challenge 2011”, [Online: www.cinc.org/archives/2011/pdf/0273.pdf]

[12] http://mobithinking.com, “Global mobile statistics 2012 Part A: Mobile subscribers; handset market share; mobile operators”, Dec 2012 [Online: http://mobithinking.com/mobile-marketing-tools/latest-mobile-stats/a#subscribers]

[13] Physionet,"PhysioNet/Computing in Cardiology Challenge 2011", Last updated August 2012 [Online: http://physionet.org/challenge/2011/]

[14] Sana, Innovation Global mHealth, [Online: http://sana.mit.edu]

[15] Electrocardiography,"Electrocardiography", Wikipedia. [Online: http://en.wikipedia.org/wiki/Electrocardiography]

[16] Emergency Medical Techinician Resource, " 12-Lead ECG Placement".[Online: http://www.emtresource.com/resources/ecg/12-lead-ecg-placement]

[17] National Institute of Medical Statistics, Indian Council of Medical Research (ICMR), 2009, IDSP Non-Communicable Disease Risk Factors Survey, Phase-I States of India, 2007-08. National Institute of Medical Statistics and Division of Non-Communicable Diseases, Indian Council of Medical Research, New Delhi, India.

[18] R. F. Yazicioglu, S. Kim, T. Torfs, P. Merken, C. Van Hoof, "A 30 µW analog signal processor ASIC for biomedical signal monitoring" IEEE ISSCC Dig. Tech. Papers pp.124-125, Feb 2010

[19] Wei-Ming Chen; Wen-Chia Yang; Tzung-Yun Tsai; Herming Chiueh; Chung-Yu Wu, "The design of CMOS general-purpose analog front-end circuit with tunable gain and bandwidth for biopotential signal recording systems," Engineering in Medicine and Biology Society,EMBC, 2011 Annual International Conference of the IEEE , vol., no., pp.4784,4787, Aug. 30 2011-Sept. 3 2011

[20] Dae-Seok Lee, Sachin Bhardwaj, Esko Alasaarela and Wan-Young Chung, "An ECG Analysis on Sensor Node for Reducing Traffic Overload in u-Healthcare with Wireless Sensor Network" IEEE Sensors Conference,, pp.256-259, July 2007.

[21] Xiuquan Fu, Weihong Chen, Shuming Ye, Yuewen Tu, Yawei Tang, Dingli Li, Hang Chen, and Kai Jiang, "A Wireless Implantable Sensor Network System for In Vivo Monitoring of Physiological Signals" IEEE Transactions on Biomedical Engineering, vol.15, no.4, pp.577-584, July 2011.

[22] Chin-Lung Yang, Chi-Lin Tsai, Kuo-Tsun Cheng, and Sheng-Hao Chen, "Low-Invasive Implantable Devices of Low-Power Consumption Using High-Efficiency Antennas for Cloud Health Care" IEEE Journal on emerging and selected topics in circuits and systems, vol.2, no.1, pp.14-23, July 2011.

[23] Bogdanova I., Rincon F., Atienza D., "A multi-lead ECG classification based on random projection features" International Conference on Acoustics, Speech, and Signal Processing pp.625-628, March 2012.

[24] Zhang C.F., Tae-Wuk Bae, "VLSI Friendly ECG QRS Complex Detector for Body Sensor Networks " IEEE Journal on emerging and selected topics in circuits and systems vol.2, no.1, pp.52-59, March 2012

[25] Refet Firat Yazicioglu, Patrick Merken, Robert Puers, and Chris Van Hoof, "A 60 µW 60 nV/ Hz Readout Front-End for Portable Biopotential Acquisition Systems" IEEE Journal of Solid-State Circuits vol.42, no.5, pp.1100-1110, May 2007

[26] Mneimneh M.A., Yaz E.E., Johnson M.T., Povinelli R.J., "An adaptive kalman filter for removing baseline wandering in ECG signals", Computers in Cardiology, 2006 , pp.253-256, Sept. 2006

[27] Nacera M., Samir B., Mokhtar A., "Hardware-software preprocessing platform for high immunity ECG recording", International Conference on Communications, Computing and Control Applications (CCCA), 2011, pp.1-4, March 2011

[28] Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov PCh, Mark RG, Mietus JE, Moody GB, Peng C-K, Stanley HE. PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals. Circulation 101(23):e215-e220 [Circulation Electronic Pages; http://circ.ahajournals.org/cgi/content/full/101/23/e215]; 2000 (June 13). PMID: 10851218; doi: 10.1161/01.CIR.101.23.e215

[29] Bousseljot, R.; Kreiseler, D.; Schnabel, A.; ,Nutzung der EKGSignaldatenbank CARDIODAT der PTB ber das Internet, Biomedizinische Technik, Band 40, Ergnzungsband 1 (1995) S 317

[30] Dawson, D., et al,"Linear affine transformations between 3-lead (Frank XYZ leads) vectorcardiogram and 12-lead electrocardiogram signals" Journal of Electrocardiology, vol.42, no.6, pp.622-630, Dec 2009

[31] Levkov, C.L.,"Orthogonal electrocardiogram derived from the limb and chest electrodes of the conventional 12-lead system",Medical and Biological Engineering and Computing, vol. 25, no. 2, pp.155-164, March 1987

[32] Hlatky, D., et al,"Criteria for Evaluation of Novel Markers of Cardiovascular Risk." Journal of the American Heart Association, April 2009

[33] Bland J. M, Altman D. G. Measuring agreement in method comparison studies.Statistical Methods Medical Research 1999; vol 8 pp:135-160

[34] Cardiac monitors, heart rate meters, and alarms [American National Standard (ANSI/AAMI EC13:2002)]. Arlington, VA: Association for the Advancement of Medical Instrumentation, 2002.

[35] Chapters 3, 4, Marvasti, Farokh. Nonuniform Sampling: theory and practice, 2001. Springer. Google Books.

[36] Richard G. Baraniuk,"Compressive Sensing: Lecture Notes" IEEE Signal Processing Magazine, July 2007

[37] Srikanth Reddy, D.S., Tamboli, R.R., Jana, S., "Universal nonuniform sampling of ECG signals: Opportunities and obstacles, "Biomedical Engineering International Conference (BMEiCON), 2012 , vol., no., pp.1,5, 5-7 Dec. 2012